INVESTIGATIONS OF NUTRIENT STRESS IN SOME FORESTRY AREAS OF SOUTH AFRICA

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Declaration

I the undersigned hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Abstract

One of the greatest limitations to the productivity of a plantation forest is poor nutrient status of the soil. Empirical application of corrective treatments are marginally successful in some cases, but because of limited understanding of the soil-tree system, most nutritional problems go unnoticed or are accepted as a conceivable growth constraint. The aim of this investigation was to identify nutrient growth problems through field observations and to determine means of confirming these nutrient imbalances.

Poor and abnormal growth of pine trees in the following areas were investigated:

(i) The North Eastern Cape: Ugie and Maclear Districts

(ii) The Natal Midlands: Mooi River area

(iii) Mpumalanga: Graskop and Kaapsche Hoop areas

(iv) Southwestern Cape: Jonkershoek Plantation

The study was conducted as nursery trials at the University of Stellenbosch and field trials at the various locations. Soils from the different regions were collected and used as growing media to test the growth response of five timber species (*Pinus patula, P. elliottii, P. taeda, P. greggii* and *Eucalyptus nitens*) under controlled conditions to various nutrient treatments. Indicator plants (cauliflower and soya) were included in these bio-assays. In the field trials nutrients were applied to seedlings and established stands of various ages by means of foliar and soil application.

In the nursery trials and the trials where seedlings were planted in the field, plant performance was measured by quantitative means. The reaction of established stands to nutrient treatments were however less vigorous and qualitative means (e.g. colour changes) were used for assessment.

Field observations in the North Eastern Cape and the Natal Midlands indicated possible boron, iron and molybdenum deficiencies and thus the work concentrates on these elements. Foliar and soil analyses reinforced these observations with marginal to deficient levels for boron and molybdenum being detected. The yellowing of foliage during the dry season was symptomatic of ineffective nitrogen assimilation and

pointed to a molybdenum deficiency while seasonal growth tip dieback, resin exudation, sinuous tree limbs and bushy trees were classical boron deficiency symptoms. Potted trials indicated positive reaction to the application of boron and molybdenum deficiency symptoms were observed on indicator plants. Conclusive evidence of a boron deficiency in some of the pot trials, the planted field trials and the tree evaluation field trials remain elusive due to toxicity experienced as a result of an over-application of the nutrient. The occurrence of multiple deficiencies (phosphorous and calcium) further complicated the findings.

The Mpumalanga observations indicated severe nutrient imbalance due to manganese toxicity (strong iron antagonism). The discolouring of the foliage on some sites towards the end of the winter was thought to be an induced molybdenum deficiency on the weathered and acidic red soils. Positive reaction to molybdenum application occurred in a single tree evaluation trial, but because of soil oxidisation during collection, the effect of manganese toxicity was diluted in the pot trials. Foliar analyses indicated that foliar application of iron was unsuccessful and that other means should be considered to ensure uptake of this nutrient.

Opsomming

Die lae vrugbaarheid van grond is een van die grootste beperkings tot die produktiwiteit van plantasie bosbou. Empiriese toedienings van kunsmisstowwe is in sekere gevalle suksesvol tot die bekamping van onvrugbaarheid. Weens gebrekkige kennis t.o.v die grond-boom sisteem word baie van die voedingstof probleme egter onkundig oorgeslaan of word dit as natuurlike beperking in die produksie konteks aanvaar. Die doel van hierdie ondersoek was om swak boomgroei in die veld waar te neem en om bevestigende metodes te vind waarmee hierdie probleme as voedingstoftekorte geëien kan word.

Swak en abnormale boomgroei van denne is in die volgende gebiede ondersoek:

(i) Die Noordoos Kaap : Ugie- en Maclear Distrikte

(ii) Die Natal Middelande: Mooirivier area

(iii) Mpumalanga: Graskop- en Kaapsche Hoop areas

(iv) Suidwes Kaap: Jonkershoek Plantasie

Die ondersoek is uitgevoer as kwekery proewe by die Universiteit van Stellenbosch en as veldproewe in die onderskeie areas. Grond is uit die verskilende gebiede versamel en as groeimeduim gebruik om die groei-reaksie van vyf verskillende houtspesies (*Pinus patula, P. elliottii, P. taeda, P. greggii* en *Eucalyptus nitens*) onder beheerde klimaatsomstandighede te ondersoek. Daar is ook gebruik gemaak van indikator spesies (blomkool en soya) vir diagnose van visuele tekort simptome. Beide saailinge en reeds gevestigde bome is in die veldproewe gebruik. Voedingstowwe is by aanplanting toegedien, of in die geval van groter bome, as blaar- of grondtoedienings.

Waar dit moontlik was (meestal in die geval van die saailinge) is die reaksie op die toegediende voedingstowwe met kwantitatiewe metodes bepaal. Daar moes egter van alternatiewe kwalitatiewe metodes gebruik gemaak word om die reaksie by die ouer en groter bome te bepaal. Gevolglik is verandering in bladkleur t.o.v. 'n basiskleur onder andere as maatstaf gebruik.

Waarnemings van swak boomgroei in die Noordoos Kaap en die Natal Middelande het gedui op moontlike boor, yster en/of molibdeen tekorte. Lae vlakke van hierdie elemente in blaar- en grondanalises het hierdie waarnemings bevestig. Die geel verkleuring van die naalde gedurende die droë seisoen is simptomaties van oneffektiewe stikstof assimilasie en dui op 'n molibdeen tekort. Die waarneming van seisoenale terugsterwing van groeipunte, gebuigde stamme en takke, gomuitskeiding en bome met bosagtige voorkoms is eienskappe van 'n boor tekort. In die potproewe was daar positiewe reaksie op die toediening van boor en tekort simptome van molibdeen is in die indikator plante waargeneem. In van die potproewe, die saailing veldproewe en ander veldproewe kon daar egter nie uitsluitsel tot die effektiwiteit van boor gevind word nie aangesien toedienings te heftig was en toksisiteit ervaar is. Diagnose van enkel element voedingstof tekorte word bemoeilik deur van die proewe wat ook dui op veelvoudige voedingstof tekorte (veral fosfaat en kalsium).

In Mpumalanga is daar waargeneem dat drastiese voedingstof wanbalanse a.g.v. mangaan toksisiteit aanwesig is (veral 'n sterk Fe antagonisme). Die bladverkleuring op sekere proefopstande aan die einde van die winter is ook 'n aanduiding van geïnduseerde molibdeen tekorte wat op die verweerde en suur rooi gronde van die omgewing verwag kan word. Daar was dan ook positiewe reaksie op die toediening van molibdeen, hoewel slegs by een proefopstand. Die inherente nadeel van potproewe is op die mangaanryk gronde geopenbaar deurdat belugting (gedurende grond versameling) die effek van mangaan toksisiteit verminder het. Die gebruik van blaaranalises is ook voordelig aangewend om te bepaal dat die toediening van yster as blaartoediening onsuksesvol was en dat ander metodes ondersoek moet word om opname van die element te verseker.

Table of contents

List of Tables

List of Tables (continued)

List of Tables (continued)

List of Figures

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1. Introduction

In South Africa marginal growing areas have historically been reserved for forestry. These areas are generally of low fertility and poor growing conditions have resulted in plantations with extended rotational cycles and crops of inferior quality. The resultant nutritional stress was however not only limited to these areas but when more fertile areas (including ex-agricultural lands) throughout the summer rainfall region were recently afforested, poor growth performance was also attributed to nutritional problems.

There are definite areas in South Africa where acute nutrient shortages and or toxicities can contribute to poor growth of forest trees. Through nutritional awareness these areas can be identified and accordingly managed to increase the fertility of the forest site to the ultimate profit of the forest manager.

Generic remedies for forest fertility problems are inadvertently addressed by the application of nitrogen, phosphorous and/ or potassium in various ratios and in various amounts from different fertiliser sources. These fertilisers are applied on a cost/profit basis and not always to alleviate specific nutrient problems. Nutrition in a forest is of such a nature that balance of all nutrients is required for optimum growth. Optimum growth does in some cases fall outside the economic profit margin and forest managers do not consider the need for application of minor nutrients for percentage point increases in growth. As a consequence, fertility research beyond the application of nitrogen, phosphorous and potassium has seldom been conducted. The known occurrence of, for instance, micro-nutrient deficiencies in South African forestry areas is limited to boron, copper and zinc deficiencies in the sandy soils of Zululand and the manganese deficient soils of the south-western Cape (Anon, 1990).

The aim of this study was to observe nutrient stress in some plantation growing areas of South Africa. Trials have been done in the field and in a nursery environment to determine the cause of the observed nutrient stress. Soil and foliar analyses would confirm the findings of these trials. A compilation of literature data of critical soil and foliar nutrient content for some of the tree species grown in South Africa are thus needed (included as *APPENDIX 3*). Other methods were also used to define and characterize

nutrient stress. Nutrient stress is not only a concept of fertility shortage but includes aspects of imbalance and toxicity. A study in this area requires knowledge of the various nutrients, of the trees that utilize them and of methods to measure nutrient availability.

Mineral nutrition of major agricultural crops has been studied for a length of time and most of these findings are applicable to forestry. The greatest difference between the forest and agricultural crop is the scale of time that influences the cycling of nutrients. The rate of nutrient cycling of a forest change within the rotational lifetime and the litter layer and the soil become an important part in the nutrient system. The dynamics and nutrient change of a forest system can be seen with the afforestation of virgin areas where nutrient balance between sources and sinks are only established after a period of years.

In this study the various nutrients are discussed as components of minerals, of soil and how they ultimately affect fertility. The importance of each nutrient to the well being of the tree is discussed and symptoms of deficiency and toxicity are investigated. Fertility of a soil is a complex and dynamic system with the availability of nutrients to a tree being dependent on various factors such as temperature, soil water content, soil texture, soil structure, soil acidity, plant hormones and tree species. Each nutrient is unique in its behaviour to various environmental conditions and these major influences on soil fertility are referred to.

The functions of the various nutrients are summarised in a separate chapter. It is often possible to determine cause and effect when the function of a nutrient within the plant is known. This assists and facilitates in the diagnosis of various symptoms.

The rate of nutrient circulation between the plant and the soil influences the cyclic occurrence of seasonal nutrient stress. A chapter on nutrient cycling is thus needed to determine the location of nutrient sinks and to highlight the areas of nutrient depletion. Forecasting of nutrient movement within the tree allows greater understanding of nutrient measurements that assist in the determination of nutrient balance. Knowledge of the changing nutrient content of senescent, juvenile and mature foliage helps with the interpretation of foliar analyses and critical nutrient levels.

In the chapter on the nature of nutrient stress the conditions that generally contribute to fertility are discussed. Environmental and ecological conditions may affect nutrition by singular influence on a specific nutrient, but in most cases the environment acts on a whole set of nutrients. The fertility of a site is greatly influenced by the soil that in turn interacts at various levels with the environment and the ecology. Soil is discussed as an encompassing factor that includes elements of climate and how it affects soil conditions.

The effect of weeds on nutrient stress has become a problem where ex-agricultural lands have been afforested. This has various silvicultural implications and suspected alleleopathic effect and nutrient interaction is investigated. Weeds are natural competitors for light, water and nutrients and add to the growth stress of seedlings. Mortality and poor growth of forest seedlings have been directly attributed to the effect of weeds.

The identification of nutrient imbalances has further proved to be problematic. There are ambiguous symptoms of nutrient stress and in some cases remedies are only based on empirical knowledge. There are however certain methods whereby nutrient imbalances can be identified. Nutrient stress is measured in various ways with successful diagnosis based on many factors. Visual diagnosis of deficiency symptoms is regarded as the initial procedure in the determination of nutrient stress and nutrient disorder diagnostic keys for pines and eucalypts are included in the study. Chlorosis is the most common symptom of mineral nutrient deficiency and thus colour is used as a distinct measure of nutrient status.

Indistinct visual deficiency symptoms complicate nutrient stress determination and other methods of measurement are discussed and used. In this study field diagnosis by use of visual symptoms were assisted by soil analyses and foliar analyses. Bio-assays were mostly used in the nursery trials. This is an easy and cost-effective way of controlling environmental conditions and it is regarded as essential to preliminary investigation of nutrient stress in problem areas. Indicator trials with cauliflower and soya were used for the visual (biomass determination also included) determination of visual deficiency symptoms.

The values of elemental concentrations that are acquired from the foliar analyses are often used as bases for the confirmation of a nutrient deficiency. The amount of nutrients in the different parts of the tree however varies too such an extent that comparison to certain

values of adequacy could be deceiving. The use of critical levels for the measure of nutrient deficiency should thus be specific for a selected species, growth stage and forest type. A literature study of critical foliar nutrient levels for the most important timber species was compiled as *APPENDIX 3*. This was used to compare measured field values.

In the confirmation of nutrient stress, two methods (DRIS and vector analysis) are discussed. These methods were however not applied in the study due to cost of analyses required for vector analyses and the absence of a suitable database for DRIS analyses. These are acceptable methods for nutritional studies and worthy of inclusion and discussion.

The obvious conclusion to an investigation of nutrient stress in a region or area is a map with indications of nutrient deficiencies and/or toxicities. An elementary map that covers most of the forestry regions in South Africa was thus constructed. Recorded and referenced sites are indicated, also with observations by foresters, researchers and the author. Most of the included cases have been affirmed.

There is limited knowledge on the application of nutrients to forests trees. Most of the literature is occupied by the application of nitrogen, phosphorous and potassium. Rates of nutrient application were a major concern in this study and toxicity in the application of specifically boron was expected. In an investigation of this nature it is however of more concern that nutrients are oversupplied and to ensure that at least some nutrients are absorbed by the plants, and as a result nutrients were applied at a rate that was more than adequate.

Investigations of nutrient stress in the pot trials and in the field are mostly concentrated on particular nutrients that fit field diagnosed problems. Most of the trials contained boron, molybdenum and iron but other nutrients were also included. It would be incorrect to assume that these are the only nutrients that are the cause of severe growth problems, but it was a conceivable point of departure. Multiple deficiencies were expected in all the areas and thus positive reaction to the application to any of these nutrients is a step in the right direction. The trials are discussed by region of investigation. Nursery trials and field trials of the same area are included under the same sub-headings. This is done to establish how problems are bound to specific regions and to indicate the similarity and differences

between the growth problems throughout the forestry regions. Differences in soil fertility influence the onset of deficiency symptoms and the length of the pot trials varied according to the specific nutrient problems. Thus dates of trial initiation and the length of the pot trials do not concur.

Foliar analyses are used to determine the success of nutrient application in the field. The monitoring of the change in foliage colour assisted this method. In the established stands a change in poor tree form to good tree form cannot be expected from nutrient application and the method most suited to the measurement of reaction to the applied nutrients is thus through foliage colour change. Unfortunately means of foliar spectrum analyses were not available and subjective colour measurements were made. In some instances this however proved to be a useful means for the determination of nutrient stress.

2. Literature study

2.1 Mineral nutrition

A living plant consists of organic matter (27%), water (70%) and minerals (3%) (Mengel and Kirkby, 1978). The mineral component allows for the building of organic material and influences all chemical processes within a plant. The mineral uptake of any plant is controlled by the specific, genetically fixed nutrient uptake potential of that plant and this is the reason that some nutrients are absorbed at levels higher than others. The levels of nitrogen and potassium is for example ten times higher than that of phosphorus and magnesium, and that again is a hundred to a thousand times the amount of micro-nutrients present in the plant (Mengel and Kirkby, 1981).

The growth of a plant is determined by restraining factors of undesirable growth conditions (e.g. drought) or limited access to nutrients. From a nutritional point of view it is required that the restraining factors of growth are known, how they can be overcome, what increase in growth after amelioration can be achieved and what the following restraining factors then will be. This is in accordance with the Law of Minimum (formulated by Justus von Liebig, 1863) (Marschner, 1997) that states that the yield of a

crop is limited by the factor in growth that is present in least quantity to the requirement of the crop.

A low concentration of a nutrient in plant tissue can be limiting and is referred to as being deficient. At the lower levels of deficiencies there may be visual indications of deficiency symptoms that can be used in the diagnosis of the nutrient problem. A characteristic pattern exists between the mineral nutrient uptake and the growth of a plant (*FIGURE 2.1)*.

These patterns vary between plants and are dependent, amongst others, on the type of nutrient measured. Generally the higher the concentration of a nutrient, the higher the resultant yield. The increase in yield however reaches an optimum level (at different concentrations for different nutrients and plant species) and ultimately the yield decreases at a point where concentrations of a nutrient have reached toxic levels. The range between sufficient and toxic concentrations may be very narrow, as in the case of boron (B) that may be represented by *FIGURE 2.1(b)*.

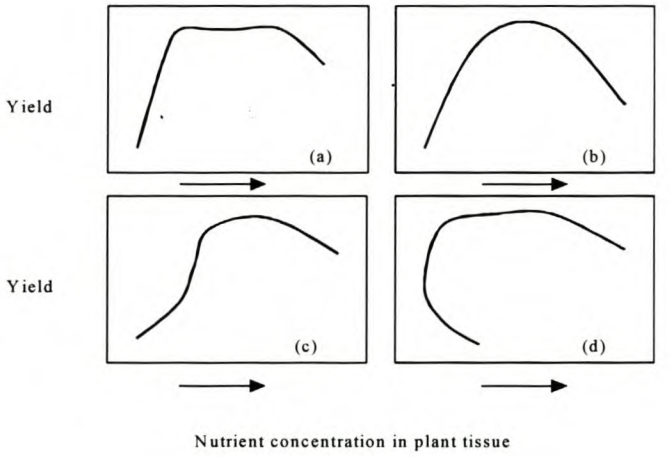


Figure 2.1. *The relationship between nutrient concentrations and plant growth*

A condition that is difficult to visually diagnose is called hidden hunger. Landis (1984) explains this concept (FIGURE 2.2) by using the relationship in *FIGURE 2.1 (d)*. At low concentrations of a particular nutrient the plant may exhibit symptoms of a deficiency but

at a slightly higher concentration, where the nutrient is still deficient, the symptoms may disappear.

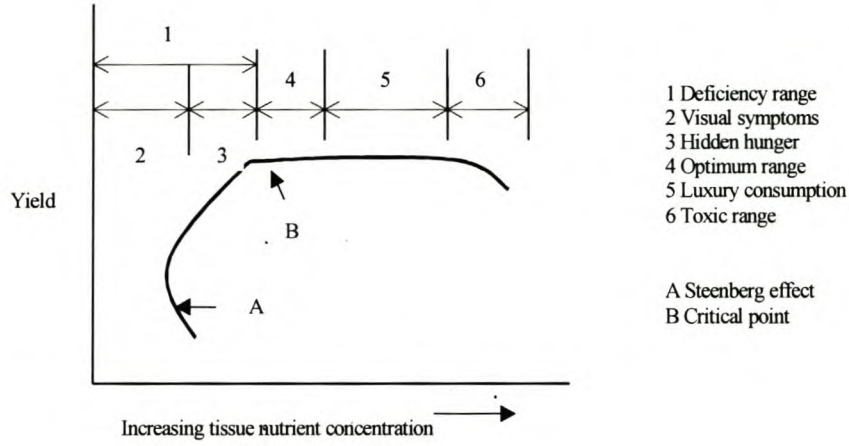


Figure 2.2. *Hypothetical relationship between mineral nutrient concentration and growth (after Landis, 1984)*

In the nutrient uptake curve of *FIGURE 2.2,* the section A depicts the effect of nutrient addition to severely deficient plants. This is called the Steenberg effect where rapid growth (after nutrient stress is relieved) results in a short term reduction of nutrient concentration (Landis, 1984). The critical point (*B*) marks the point of nutrient concentration where the growth rates decreases to an optimum rate. At this point 95% of the maximum yield is achieved. Further uptake of nutrients result in luxury consumption and little improvement in yield. High concentrations of certain nutrients negatively affect the growth of plants and at these concentrations the nutrient is said to be toxic.

2.2 Nutrient elements in forest systems

A plant needs organic and inorganic compounds for growth and for the functioning of vital processes. Most of the elements that are needed by the plants are inorganic of nature. There are at least 16 elements (*TABLE 2.1)* that have been described as essential to the growth and development of plants. To the list of essential elements chlorine (Cl), silicon (Si) and sodium (Na) are sometimes added. This list may increase as improved technology allows for the measurement of smaller amounts of nutrients.

For an element to be essential it is defined as being required for the normal life cycle of an organism and whose function cannot be substituted by other chemical compounds (Van den Driessche, 1991; Mengel and Kirkby, 1981). Without an essential element it is impossible for the plant to complete its normal vegetative and/or reproductive cycle and that deficiency symptoms of a specific element can only be rectified by the addition of that particular element.

The plant nutrients that are required in relatively high amounts are labelled as macronutrients and the nutrients that are needed in lesser amounts as micronutrients. The actual distinction between the macro- and micronutrients (on the bases of relative concentration) have been described as rather arbitrary by various authors (Epstein, 1972, Kramer and Kozlowski, 1979). The amount of nutrients that are present in a plant does not qualify as means of classification. Some nutrients may be present in high concentrations (like aluminium (Al), nickel (Ni), selenium (Si) and fluoride (F)), but have no positive or, in contrast, toxic effect on the growth of a plant. Grouping of nutrients according to their biochemical behaviour and their physiological function has been done by Mengel and Kirby (1981) (*TABLE 2.1)* :

- Group I : this group includes most of the organic plant material. Carbon (C), oxygen (O) and hydrogen (H) are taken up from the atmosphere as CO_2 and from the soil solution as HCO_3^-. The assimilation of C and O results in the building of carboxylic groups and with H, that is reduced (photolysis) from H_2O in the process of photosynthesis, these elements are known as the principal components of macromolecular compounds that ultimately make up cell wall and cell organelles. Nitrogen is taken up as a gas (N_2) from the atmosphere (in symbiotic relationships with microorganisms such as *Rhizobium* and *Actinomyces)* or as nitrate (NO_3^-) or as ammonium (NH_4^+) ions from the soil. Assimilation of NO_3^- and NH_4^+ is done in complicated amination processes, as is N_2 after initial reduction to NH_3. Sulphur (S) from the soil solution (SO_4^{2-}) or from the atmosphere (SO_2) is assimilated in similar ways to that of N. The elements in the first group are all thus assimilated by complex physiological reactions as the main constituents into the organic plant material.
- Group II : The elements in this group (phosphorus (P), boron (B) and silicon (Si)) are all absorbed as inorganic anions or as acids. In the plant largely hydroxyl groups

(OH-) of sugars that form phosphate-, borate- and silicate-esters bind them. They also occur as inorganic anions or acids in the plant cells.

- Group III : Potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), manganese (Mn) and chlorine (Cl) are taken up from the soil solution in their caonic form and are present in the cell as free ions or they are adsorbed to indiffusible organic anions.
- Group IV : Iron (Fe), copper (Cu), zinc (Zn) and molybdenum (Mo) occur in the plant as metal chelates (Mengel and Kirby, 1981).

Many nutrients that are not required for plant growth have been found in plant tissue. These nutrients can be seen as the residue of the large volume of water that passes through the plant during transpiration and that are passively absorbed from the soil solution (Kramer and Kozlowski, 1979). Generally, the macronutrients are incorporated into cellular constituents (with Ca as the exception), but they may also serve physiological functions as coenzymes or enzyme activators. Micronutrients are not a significant part of the structural plant component, but serve in various metabolic functions (Landis, 1984).

Table 2.1. *Classification of plant nutrients, ionic forms in which they are absorbed and grouped according to Mengel and Kirby (1981) and concentration in healthy plant tissue (Epstein, 1972).*

Nutrient element	**Ionic form**	**Concentration**	**Group**
From air and water		%	
C	CO_2, HCO_3^-	45	I
H	HCO_3^-	45	I
O	CO_2, HCO_3^-, O_2	6	I
Macronutrients		%	
N	NH_4^+, NO_3^-	1.5	I
P	$H_2PO_4^-$, HPO_4^{2-}	0.2	II
K	K^+	1.0	III
Ca	Ca^{2+}	0.5	III
Mg	Mg^{2+}	0.2	III
S	SO_4^{2-}	0.1	I
Micronutrients		ppm	
Fe	Fe^{2+}	100	IV
Mn	Mn^{2+}	50	III
Zn	Zn^{2+}	20	IV
Cu	Cu^{2+}	6	IV
B	H_3BO_3, $H_2BO_3^-$, HBO_3^{2-}, BO_3^{3-}	20	II
Cl	Cl^-	100	III
Mo	MoO_4^{2-}	0.1	IV

2.2.1 Nitrogen

2.2.1.1 Geochemistry

Nitrogen (N) is an element that is widely distributed in nature. The largest quantity is found in a fixed form in the earth's crust in rocks and sediments and not in the atmosphere as is commonly believed. The atmosphere contains about 80 % of the N that is in circulation (mostly as N_2), but that amounts to only 2 % of N on earth that is usually not in plant available form.

Nitrogen is found in the soil in the form of molecular nitrogen (N_2), gaseous compounds (NH_3, N_2O, NO, NO_2) or as inorganic ions (NH_4^+, NO_3^-, NO_2^-). The N in the soil only accounts for a small proportion of the lithospheric nitrogen that is available to plants. The inorganic N fraction of the soil (the part not available to plants) can be constituents of primary silicates in positions that are normally occupied by potassium, it may be part of secondary aluminiumsilicate clay minerals (e.g. illite or vermiculite) or it may be in the form of a secondary mineral, taranakite ($(K,NH_4)_3Al_5H_6(PO_4)_8.18H_2O$) (Epstein, 1972; Mengel and Kirkby, 1981).

The plant absorbs most of the N in the forms of ammonium (NH_4^+) or nitrate (NO_3^-). These ions are the products of the mineralisation process of organic N through the action of various micro-organisms. The circulation of N through a forest system has been widely studied (Gosz, 1984) and it has been found that weathering of the N containing rocks contributes a smaller fraction than the fixation by plants and bacteria or through mineralisation. The surface layer of a forest (leaf litter, fallen branches, etc.) is the origin of organic material that contains organic nitrogen that is ultimately converted to ammonium and/or nitrate. The depth of this layer is an indication of fertility, and loss of this source through management practices like burning could result in N deficiencies.

The N content of soil is measured as total nitrogen and is not an indication of plant available nitrogen. Clayey soils have a greater N content than soil of more sandy texture and thus deficiencies are expected on sandy soils with no or little organic litter layers.

This has been observed by Ellis (1997) on the sandy and leached soils of the Western Cape Province (Grabouw area).

The preference of plants to ammonium or nitrate uptake depends on different factors. An important factor is the species itself. Calcifuge plants (plants adapted to acid soils) and plants adapted to low redox potential (wetland rice) have a preference for ammonium (NH_4^+). Nitrate (NO_3^-) absorption is preferred by plants adapted to high pH (calcareous) soils and they are referred to as calcicoles (Marschner, 1997). Of the total amount of cations and anions that are taken up by plants, more than 80 % consists of ammonium and nitrate and consequently the form of nitrogen has a strong impact on the uptake of other nutrients, the cellular pH and the rhizosphere pH. Different uptake rates of cations and anions require the regulation of cellular pH and compensations of electrical charges. Optimal growth for any species includes a balance between ammonium and nitrate uptake. When an imbalance occurs maintenance of the cellular pH must take place at the cost of photosynthates that in the end reflects as poor growth.

Assimilation of nitrate occurs after the reduction to nitrite (NO_2^-) through the process of nitrate reductase (of which molybdenum forms an integral part) and then to ammonia through nitrite reductase in the chloroplast (Marschner, 1997). Nitrate reductase activity is very low in molybdenum deficient plants and this results in a nitrogen deficiency if the plant does not absorb enough ammonium nitrogen ($N\text{-}NH_4^+$). Ammonium nitrogen is assimilated by the roots into amino acids and amides and these products are biosynthesised into proteins.

Most of the soil N is present in organic form that is converted (biologically) to nitrate (NO_3^-) which is weakly held in the soil. There is a large variation of nitrate (NO_3^-) content in the soil during the growing season, and the fluctuation of nitrate (NO_3^-) in the soil is the greatest for all nutrients.

2.2.1.2 Factors affecting the availability of nitrogen

As the source of N is largely organic of nature, the accumulation and absorption of nitrogen from the soil is largely dependent on the vegetation that occurs and the influence of the environment on the nutrient cycles.

- Carbon-nitrogen ratio

Carbon is contained as source of energy in carbohydrates and affects the tempo and amount of N mineralisation in that the micro-organism populations explode as reaction to higher energy levels in the soil. In a soil with high carbon to N levels the bacteria require a lot of nitrogen and a temporary reduction of soil N might occur. This is called immobilisation. The following relationships have been defined:

(i) C:N > 30:1 – immobilisation takes place

(ii) C:N < 15:1 – net mineralisation takes place

The C:N ratio in organic materials range between 130:1 and 475:1 in the bark and 1000:1 for the wood of conifers (Ellis, 1997). A humic topsoil (as found in parts of the Natal and Eastern Cape grasslands) has a C:N ratio range of between 10:1 and 20:1 (Smith and Van Huyssteen, 1992).

- Soil

Changes in the pH of a soil does not influence the ionic type of N to be found in the soil as much as it influences changes in the pH sensitive bacteria population. At high pH (above 7,5) the suboptimal working of nitrification bacteria can impede the nitrification process and can result in nitrite (NO_2^-) toxicity (Marschner, 1997), but this is unlikely in a plantation soil.

- Soil water

Ion absorption in the nitrogen-feeding zone can be impaired by drought stress by a decline in nitrate reductase activity. A deficiency in nitrogen may thus be the long-term effect of drought stress (Hale and Orcutt, 1987).

Adequate soil water content allows for abundant growth and thus a higher rate of litter accumulation and organic material. This is the case where depressions occur in the landscape and on cooler southern slopes. Elevated terrain usually contains less organic material with the exception in higher rainfall and cool areas (Ellis, 1997).

- Interaction with other nutrients

See sections pertaining to other nutrients.

2.2.1.3 Visual symptoms of nutrient stress

Nitrogen deficiencies are characterised by poor growth. This is caused by a decrease in photosynthesis due to chloroplast collapse and a disturbance of chloroplast development.

- Conifers

There is general chlorosis but this is more acute on the older leaves. The younger leaves remain greener because of transportation of soluble forms of N from the older leaves (Lyle, 1969). The yellow colouring is caused by a decrease in chlorophyll production (Salisbury and Ross, 1985; Mengel and Kirkby, 1981).

The needles become more stunted with increasing severity of deficiency, the needles are stiff, yellow-green with purple tipping advancing to necrosis at the end of a growing season (Timmer, 1991). In New Zealand N deficiency of *P. radiata* on sandy soils were marked by pale coloured foliage and very fine branching (Will, 1978, Will, 1985; Reuter and Robinson, 1997).

- Broadleaves

At the onset of the deficiency, the interveinal areas of the mature leaves turn pale green. This intensifies towards the expanding leaves and the oldest leaves may develop necrotic spots with purple margins and bleached centers. The symptoms can be differentiated from a sulphur deficiency where chlorosis spreads from young to older leaves (Dell *et al.*, 1995, Dell, 1996). On seedlings, the symptoms spread rapidly from old to young leaves (Reuter and Robinson, 1997).

Toxicities of N do occur and may cause an increase in the shoot: root ratio. The leaves turn dark green with an excess of N. A high N level in the foliage is correlated with an increase in the size and number of lateral roots and poorer stem forms have been observed in pines (De Ronde, 1992).

2.2.2 Phosphorus

2.2.2.1 Geochemistry

Phosphorus in the soil mainly occurs as orthophosphates at a range of between 0.02 and 0.15 %. Phosphate minerals in the soil have been identified, of which apatite ($CaPO_4$) is the most common mineral found. The form of apatite varies from the fluorapatite ($Ca(PO_4)_2.F_2$) and chlorapatite ($Ca(PO_4)_2.Cl_2$) from suspected primary origin and hydroxyapatite ($Ca(PO_4)_2$. $Ca(OH)_2$) from secondary depositions. (Megel and Kirby, 1981).

Apatite is the primary phosphate containing mineral and other fractions of the soil phosphates are derived from this mineral. Mengel and Kirkby (1981) categorise these fractions as the non-occluded organic phosphates and the occluded inorganic phosphates. The non-occluded fraction contains the phosphates in solution, phosphates absorbed to soil surfaces and some phosphate minerals. Iron (Fe) and aluminium (Al) minerals bind the occluded phosphate, often in a skin of iron (Fe) hydroxy compounds that results in fixation of phosphates.

The part played by phosphate minerals is a complex role where availability is determined by soil pH and the content of particularly aluminium (Al) and iron (Fe). A plant absorbs P from the soil solution that is in balance (and sourced) by a labile P reservoir that in turn is in equilibrium with a non-labile pool that is inaccessible to direct plant absorption (*FIGURE 2.3*) (Mengel and Kirkby, 1981). The P in this pool is slowly released into the labile pool but not as fast as the relationship of rapid equilibrium between the solution and labile P.

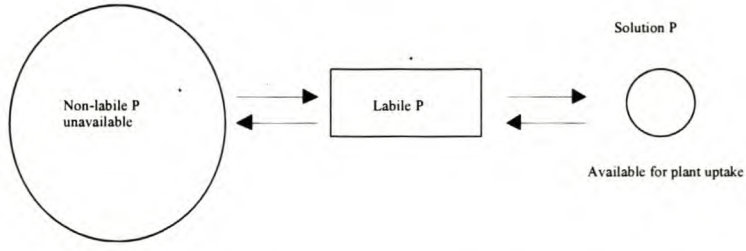


Figure 2.3. *Schematic representation of phosphate fractions in soil (Adapted from Mengel and Kirkby, 1981)*

Determining what P minerals fall in the category of the non-labile pool has been proven difficult by the fact that many P minerals contain impurities and that certain iron (Fe) and aluminium (Al) phosphates and even organic soil phosphates are slow releasers of ionic phosphates. The weathering of apatite leads to the formation of secondary minerals with increasing association with iron (Fe) and aluminium (Al). Strengite ($FePO_4.H_2O$) and variscite ($AlPO_4.H_2O$) are found in soil at pH > 4.2 (strengite) and at pH < 3.1 (variscite). Under reducing circumstances vivianite ($Fe_3(PO_4)_2.8H_2O$) can be formed with iron in the ferro form (Fe^{2+}).

The labile pool, in equilibrium with the soil solution via complicated relationships, contains most of the phosphates that are adsorbed to the surface of clay minerals, hydrous oxides, carbonates and apatites (Mengel and Kirkby, 1981). The degree and extent of adsorption rather than the amount of adsorption, influences the concentration of P in the soil solution. Phosphates in the soil solution depend on the phosphate intensity and the phosphates in the labile pool are the main component of phosphate quantity. The weathered red soils (with high phosphate adsorption capacities) found in tropical areas require a higher amount of adsorbed phosphate to ensure a similar concentration on the soil solution in comparison to a podzolic horizon. In South African forestry areas where the acid red and yellow coloured apedal soils are prevalent, strong adsorption of P occur on iron, manganese and aluminium rich soils and the phosphates are unavailable for plant uptake (Ellis, 1998). These soils are not always able to maintain the soil solution concentration and have a low buffer capacity. Treated with some form of P fertiliser results in rapid adsorption to clay mineral surfaces with little P eligible for plant uptake. Leaching of P in these soils is highly unlikely.

The relationship between adsorbed P and organic material, soil pH and the texture of the soil largely affect P in solution. In acid sands with inherent low iron, manganese and aluminium content, there are little adsorption surfaces and the phosphate content of the soil is very low. In some areas of the southern and western Cape, yellow E-horizons that have developed on sandy to sandy loam soils, phosphate is fixed and P deficiencies are common (Ellis, 1998).

The amount of P in the soil solution is low when compared to the adsorbed P. The important phosphate ions in the soil are HPO_4^{2-} and H_2PO^{1-} that are both pH dependent and thus influenced by the hydrogen (H^+) concentration in the soil. The relationship between the ions is indicaated in *EQUATION 2.1* (Mengel and Kirkby 1981).

$$HPO_4^{2-} + H^+ \longleftrightarrow H_2PO_4^- \qquad (2.1)$$

Contributions to the P in the soil solution are also made from organic origin. Although plants do not absorb organic phosphates, this fraction can be mineralised by soil micro-organisms (e.g. bacteria) and then be used by plants. Phosphate release from this source can however be so slow as to qualify as part of the non-labile fraction.

2.2.2.2 Factors affecting the availability of phosphorus

- Soil

The pH of the soil affects the balance between adsorbed P and P in solution. The optimum pH for the P in solution is at approximately pH 6. This is the mostly reason for liming a soil. Increases in soil pH as shown in *EQUATION 2.1* lead to the $H_2PO_4^{2-}$ species being dominant in more alkaline soils.

- Soil organic matter

In warm, humid areas where there is a high tempo of mineralisation (especially on virgin soils) the release of P from organic material is higher. This can be advantageous for afforestation on virgin grasslands. Increases in P mineralisation however need some form of soil cultivation for faster release of organic P. Mineralisation of organic P is pH

dependent in that the rate of P releases from sesquioxides adsorption surfaces are increased.

- Interaction with other nutrients

1. Aluminium- phosphate

In acid soils the Al concentration may reach toxic proportions and in many cases this is accompanied by P deficiencies. This has been found to be the case in the Natal Midlands where Al precipitates with phosphate on the roots of maize plants. The aluminium phosphate is a large molecule and blocks the areas of further P reception on the roots and a P deficiency is induced.

In a P adsorption study on 29 Natal soils, Bainbridge *et al.* (1995) found that more than half of these soils fell in the medium to very high P adsorption capacity category. This means that a soil with a P adsorption capacity of 500 mg P/kg will require approximately 1112.5 kg P/ha (estimated at 2.225×10^6 kg soil. ha^{-1}) to saturate the P adsorption sites of the soil in the top 15 cm. Due to the cost of P fertiliser this would not be viable.

2. Iron – phosphate

See section **2.2.7 Iron**.

2.2.2.3 Visual symptoms of nutrient stress

Phosphorus is phloem mobile and thus the first signs of a deficiency are found on the older foliage that is later redirected to younger leaves.

- Conifers

In seedlings the youngest needles are green or yellow green and the older needles purple tinged. The purple colouring deepens with severity and can spread to all needles (Timmer, 1991). The symptoms of deficiency are very variable and the whole seedling may be stunted and reduction in leaf size is often observed (Lyle, 1969).

In adult trees the crown development is underdeveloped to a thin and narrow spike. Dieback of the leader can be observed in extreme circumstances, overall the foliage is a

dull grey in colour (Will, 1985; Ellis, 1998). A thin crown has been associated with loss of older needles with the remaining needles being concentrated at the end of branches. Flaky bark and resin production have been observed in South Africa (Payn *et al.,* 1988). There is an overall lack in vigour and needles may be short in length. In colder areas the tips of needles may turn yellow and fascicles may fuse (Reuter and Robinson, 1997).

- Broadleaves

In the early stages, the mature leaves exhibit small interveinal reddish spots or patches with or without necrotic margins. The colour of the leaves varies from dark to a bluish green. In the later stages the symptoms may spread over the whole plant and in certain species the colour of the whole plant may turn red or purple. The young leaves are small, the plants stunted and the older leaves are lost at an early stage (Dell, 1996; Dell *et al.*, 1995).

Toxic levels of P can result in micronutrient deficiencies. Micronutrient deficiencies are induced when they bind with excess P. Iron chlorosis and a Zn deficiency is often encountered in areas where over-fertilisation with P has occurred (Jarvel, 1996). High levels of K counteracts P toxicities through the conversion of inorganic P to nucleic acids (Lyle, 1969).

2.2.3 Potassium

2.2.3.1 Geochemistry

The average potassium (K) content of the earth's crust is estimated at 2.3 % but this may vary according to the type of parent material and the degree of leaching. Potassium is bound in primary minerals or is present in secondary clay minerals.

The various secondary clay minerals differ in their capability to fixate K. Montmorillonite, a swelling clay with a 2:1 lattice structure, has a high density charge and thus a high potential for the fixation of K. The fixation by illite can be of such proportions that K fertilisation on such soils are ineffectual (Ellis, 1998a). In the South

African situation kaolinite clay minerals dominate most of the areas under afforestation and because of the 1:1 lattice structure, it most likely does not fixate K. This is found in weathered areas of particularly the Natal Midlands and parts of the Eastern Cape and Mpumalanga.

Soils derived from granites, gneiss and sedimentary rocks, where alkali feldspars and micas are dominant, seem to adequately supply the soil with enough K. The alkali feldspars contain 4-15% K as K_2O, the Ca-Na feldspars 0–3%, muscovite 7–11% and biotite 6–10% of K_2O. Acid sand, as derived from sandstone (Table Mountain Sandstone) contains less K than expected. These mature soils that have been subjected to strong weathering conditions are low in K and clay minerals (Mengel and Kirkby, 1981, Ellis 1998a).

Soils that are derived from basic igneous rocks like basalt, gabbro and dolerite are low in K content and growth decline due to inadequate P supply on such soils can be expected (Morris, 1983; Morris, 1986; Morris 1987, Ellis, 1998a).

The K in the soil can be partitioned into three fractions:

(i) Potassium as the structural element of soil minerals (>90%)

(ii) Potassium adsorbed in exchangeable form to soil colloids (1-3%)

(iii) Potassium in the soil solution (<1%)

To the plant the K in the soil solution is the more important fraction with the potassium ion (K^+) concentration determining the rate of diffusion towards the roots and thus uptake. A high buffer capacity of the soil (the ability to replenish K in the soil solution from the potassium adsorbed to colloid surfaces) is needed when fluctuations in the soil solution take place. In the active period of the growing season the K concentration in the soil solution show great variation and depicts the ease of absorption by the plant. During the growing season luxury feeding may take place.

2.2.3.2 Factors affecting the availability of potassium

- Soil

At low pH, K is easily leached from a soil. This is as a result of Al toxicity that may accompany this situation and results in the K cations succumbing to stronger competition (from aluminium) cations for bonding positions on soil colloids (Mengel and Kirby, 1981).

- Soil water

Soils saturated with water can negatively influence the uptake of K by the roots. Roots absorb K against an electrostatic gradient; a process that needs energy that is forthcoming from respiration. In waterlogged soils, respiration is curtailed and the absorption tempo decreases (Marschner, 1997).

- Interaction with other nutrients

1. Aluminium – potassium

In acid soils and in soils with high CEC, leaching of K is a strong possibility. Potassium on such soils has to compete with stronger multivalent cations (Al^{3+}, Ca^{2+}, Mg^{2+}) for adsorption on limited electrostatic positions and loss through the drainage can be expected and thus less K is available in the soil solution for plant uptake (Mengel and Kirby, 1981).

2. Manganese –potassium

A potassium–manganese antagonism was investigated by Schutz (1990) and Viljoen (1991) on the Mn rich soils of Mpumalanga. The uptake of K was being suppressed by the presence of high soil Mn levels. Correlation ($r = 0.54$, $p < 0.0001$) between high Mn and K levels in the soil (derived from dolomite) and low K foliar levels were found.

3. Magnesium – potassium

In agricultural field trials it has been found that K can induce or aggravate a magnesium deficiency (Epstein, 1972). The antagonism is as a result of interference with the distribution of Mg in the plant that ultimately affects photosynthesis.

2.2.3.3 Visual symptoms of nutrient stress

Potassium plays an important role in the maintenance of water regulation in plants and is highly mobile within a plant. Loss of turgor in plants is a likely deficiency symptom. Plants that suffer from a K deficiency have thinner cell walls and are more susceptible to disease attack (Mengel and Kirby, 1981). Deficiency symptoms are thus related to low temperatures and could be complicated by the presence of disease.

- Conifers

In young plants there are various symptoms of deficiency. Usually the needles are short, chlorotic with green bases. In severe cases purpling, necrosis and top dieback is found. During cold spells in winter seedlings exhibit browning and necrosis of needles rather than chlorosis (Timmer, 1991). A loss of turgor is a common symptom of plants that suffer from a K deficiency and thus frost hardiness is lessened in such seedlings (Lyle, 1969).

Similar discolouring from the tips of needles is visible on older trees – slight chlorosis followed by browning. These symptoms first appear on the older foliage. Needles last only 1.5-2 years in comparison to healthy needles that persist for 3-4 years. In warm areas a slight chlorosis in spring is followed by dark green new flush growth. In colder areas there is only the rapid development of chlorosis in the lower crown (Will, 1978; Reuter and Robinson, 1997).

- Broadleaves

Necrosis and scorching of older leaves are symptomatic of this deficiency (Reuter and Robinson, 1997). In severe cases this spreads to the younger parts of the tree. Necrotic spots form between the veins and the margins and leaf tips become scorched. There is an increase in lateral branching and older leaves abscise prematurely (Dell, 1996; Dell *et al.*, 1995).

2.2.4 Calcium

2.2.4.1 Geochemistry

Calcium (Ca) is present in a great variety of primary and secondary minerals and constitutes one of the highest composites of the earth's crust in regards to plant minerals. Apart from minerals, the divalent cation (Ca^{2+}), occurs as adsorbed calcium (to organic and inorganic soil colloids) and as calcium in the soil solution.

The primary minerals that contain Ca are aluminium- silicates, including the feldspars (e.g. anorthite, $CaAl_2Si_2O_8$,) and the amphiboles (e.g. hornblende, $[(Na,Ca)_2(Mg, Fe, Al)_5(Si,Al)_8O_{22}(OH)_2]$) and various apatite minerals $(Ca_3(PO_4)_2.Ca(Fl, Cl)_2)$. Of the secondary minerals (the calcium carbonates) calcite ($CaCO_3$), dolomite ($CaCO_3.MgCO_3$) and gypsum ($CaSO_4.2H_2O$) are found in some forestry areas of South Africa.

The Ca content of the soil depends on type of parent material, degree of weathering and the amount of leaching that has taken place. Old soils that are highly weathered and leached under humid conditions (as found on the low-base status, red, apedal soils of the eastern escarpment) are low in calcium (Ellis, 1998b). In low rainfall areas the soil content of Ca is generally higher.

The type of Ca bearing minerals that occur in a soil affect pedogenesis. Soils that are derived from Ca containing parent material (basalt and dolerite) have higher amounts of secondary clay minerals. Soils derived from calcite and dolomite may have an alkaline pH and can contain high amounts of $CaCO_3$.

The weathering and ultimately the degree of leaching in a soil are dependent on the rainfall and the formation of hydrogen ions (H^+) in the soil. These ions (and probably chelating agents) cause dissolution of minerals through the displacement of Ca in the lattice structures. The freed Ca is then adsorbed or enters the soil solution. The gradual increase in soil pH in humid areas can be attributed to the mineralisation of organic material and the formation of carbonic acid that leads to the leaching of Ca as $CaNO_3$ and $Ca(HCO_3)_2$ (Mengel and Kirkby, 1981).

2.2.4.2 Factors affecting the availability of calcium

- Soil

The problem of low Ca saturation levels that can be expected in acid, mineral soils will not come into play as the nutritional problem of absorption of other nutrients or toxicity (aluminium) will be expected first. In acid sandy soils with calcium lost to leaching, deficiencies may be expected.

At high pH calcium precipitation as carbonates and Ca deficiencies may be expected (Mengel and Kirby, 1981). In this form the Ca is not available for plant uptake. Areas where this occurs are characterised by low rainfall and thus not suitable for commercial forestry.

- Interaction with other nutrients

1. Calcium-potassium

Antagonisms with K (and to a lesser extent other cations) due to direct competition for plant absorption and carrier positions in cell membranes on root hairs, can negatively influence the uptake of other cations. High concentrations of K in the soil can thus induce a Ca deficiency (Mengel and Kirby, 1981).

2. Calcium – iron

See section **2.2.7 Iron.**

2.2.4.3 Visual symptoms of nutrient stress

Symptoms of a Ca deficiency are not commonly found. Because it is a component of cell structures (amongst other functions), it is fixed to position in the plant and thus not mobile. It is important for the development of new roots and stunting at all meristems can be expected. Deficiencies are more apparent on young foliage.

- Conifers

In young trees resin exudation (Lyle, 1969) and tip dieback or death of the terminal bud is apparent. This is accompanied by general chlorosis of the foliage (Timmer, 1991).

In *Pinus taeda* the buds and the stem tips are small and shorter leaves observed (Kozlowski, 1971). In other conifer species the young needles appear with yellow-brown tips. Exudation from buds and needles is apparent (Schultz, 1997). The sprouting of side branches gives the tree a hedged, flattened-at-the-top-appearance. Along with resin exudation, cones are produced abundantly (Reuter and Robinson, 1997).

- Broadleaves

In the early stages of a Ca deficiency, the leaf margin may be impaired and that results in the turning over of the lamina and the leaf surface becomes undulated. Increased severity of the deficiency causes tip burn of leaves and death of the leader shoots that result in multiple leaders (Dell, 1996; Dell *et al.*, 1995). The rolled margins give the leaves a distorted appearance (Reuter and Robinson, 1997).

Cases of Ca toxicity have been limited to forest nurseries where irrigation water or overliming of open-rooted nurseries resulted in induced Fe deficiencies (Ellis, 1998b). This can be alleviated by the application of Fe-chelate.

2.2.5 Magnesium

2.2.5.1 Geochemistry

The magnesium (Mg) content of the soils is dependent on the parent material and the pedogenesis of a soil. A clayey soil has generally more Mg than a sandy soil. Like K, there are the primary (non-exchangeable) and secondary mineral fractions (most are exchangeable), Mg adsorbed to soil colloids (exchangeable) and Mg in the soil solution (water-soluble magnesium) from where plant absorption occurs.

Higher levels of Mg are present in clayey soils because of easy weathering of some ferromagnesium primary minerals, e.g. olivine (Mg_2SiO_4), serpentine ($Mg_3Si_2O_5(OH)_4$,),

hornblende ($(Na, Ca)_2(Mg, Fe, Al)_5(Si,Al)_8O_{22}(OH)_2$) and biotite ($K_2(Mg, Fe)_6[(Al, Fe^{3+})_2Si_6]O_{20}(OH)_4$. Magnesium is also found in secondary clay minerals, e.g. chlorite, vermiculite, illite and montmorillonite and dolomite ($CaCO_3.MgCO_3$) (Mengel and Kirby, 1981).

The largest fraction of Mg is in the non-exchangeable form and includes the Mg in the primary minerals and most of the Mg in the secondary clay minerals. Exchangeable Mg constitutes about 5% of the total Mg content of the soil and this portion, along with the water-soluble Mg portion is of importance to the plant. Between 4–20% of the cation exchange capacity in the soil is filled by exchangeable Mg. Calcium is in the order of 80% and potassium 5%. The optimum Ca:Mg ratio in the soil is between 4:1 and 6:1. This decreases with regards to Mg with an increase in soil depth and could become 1:1 (Mengel and Kirby, 1981).

Soils derived from basalt, peridotite (coarse-grained plutonic rock) and dolomite are well supplied in Mg. Soils that are formed on serpentine contain high Mg content with a low Ca/Mg ratio on the exchange complex. These soils are however prone to Ca and other macronutrient deficiencies and heavy metal toxicities.

2.2.5.2 Factors affecting the availability of magnesium

- Soil texture

Mg from the soil solution is easily leached and consequently the lower horizons contain more Mg than surface horizons. In a coarse textured soil, or sandy soils, in high rainfall areas of Zululand and the podzolised coastal sands along the western, southern and eastern Cape areas (Ellis, 1998c) deficiencies can be expected. Highly weathered and leached laterites and podzols are generally low in Mg but accumulations in areas of depressions are possible. Mengel and Kirkby (1981) found a decrease in Mg from brown earthy soils to brown sandy soils to brown podzolic soils to podzols.

- Interactions with other nutrients

1. Calcium-magnesium

On calcareous soils where there is a large Ca:Mg ratio with a low magnesium concentration in the soil solution, plant uptake of Mg is restricted.

2. Potassium - magnesium

The plant takes up Mg in lower amounts than Ca and K with the effect that over-fertilisation of either cation can induce magnesium deficiencies. Because of the low exchange capacity of roots it has been hypothesized that preference is given to the adsorption of monovalent cations and that there is a decrease in loading of polyvalent cations (Marschner, 1997).

3. Ammonium - magnesium

Ammonium (NH_4^+) , as another monovalent cation, is in direct competition for plant uptake and under conditions of NH_4^+-N fertilisation, deficiencies in Mg can be induced. This effect is especially visible on acid soils with limited bacteria conversion of NH_4^+ to NO_3^-.

4. Manganese - magnesium

On acid soil with a high Mn content (as found in parts of Mpumalanga), manganese toxicity may induce a magnesium deficiency (Marschner, 1997). Manganese limits Mg uptake by blocking binding sites of Mg on the roots. This has an inhibiting effect on the growth of roots and shoots.

5. Aluminium - magnesium

In acid mineral soils, Al occupies the cation exchange sites of clay minerals where it replaces most of the polyvalent cations (Ca^{2+}, Mg^{2+}) that are then susceptible to leaching. Acidification of soils leads to an increase in Al solubility and toxicity and results in a decrease in concentration and uptake of Mg.

2.2.5.3 Visual symptoms of nutrient stress

A Mg deficiency is observed as chlorosis of leaves and needles because Mg is a major constituent of chlorophyll. It is a mobile nutrient and thus chlorosis of the older leaves is the first symptom of a deficiency (Salisbury and Ross, 1992).

- Conifers

Patterned chlorosis is very symptomatic of Mg deficiencies. The needle tips are yellow or orange with a yellow middle and dark green base occurring first in the older needles (Lyle, 1969; Jarvel, 1996). In *P. taeda* seedlings that suffer from Mg shortages, Lyle (1969) found that the roots are more affected than the shoots.

In seedlings, a deficiency is marked by the yellow tipping of the current needles that may deteriorate to necrosis (Timmer, 1991). In older trees, a more intense chlorosis is observed than the other nutrients (2.5 YR as opposed to 7.5 YR) with chlorosis normally starting at the needle ends. In acute deficiencies, stunted growth is observed (Schultz, 1997; Ellis, 1998c). Needles tips appear as if dipped in paint and in some seasons the stem needles become chlorotic (Reuter and Robinson, 1997).

- Broadleaves

Deficiencies are first encountered on fully expanded leaves and in severe cases it may spread to younger foliage. In some species the leaf tips become beaked with upturned margins. In the early stages there is marginal and interveinal chlorosis of mature leaves and in some cases necrotic spots may appear. The midrib and other major veins may remain green resulting in an inverted V-shaped green area (Dell, 1996; Dell *et al.*, 1995).

Toxic amounts of magnesium in the soil result in imbalances between the Ca:Mg and the K:Mg ratios. Calcium and K deficiencies can be induced.

2.2.6 Sulphur

2.2.6.1 Geochemistry

In the soil, sulphur (S) occurs in the organic and the inorganic form. Sulphur is present in a variety of minerals as sulfides (S^{2-}) or sulphates (SO_4^-). Under waterlogged conditions S occurs in reduced forms as pyrites (FeS_2) and hydrogensulfide (H_2S). In more arid environments gypsum ($CaSO_4.2H_2O$) and other salts (e.g. $MgSO_4$) can accumulate.

Under humid conditions S is either adsorbed to the soils colloids or in the soil solution. As S it is present as an anion. It is not strongly adsorbed to the soil colloids and can easily be leached from the soil (Marschner, 1997).

Sulphur, as part of the soil organic matter is an important source for plant nutrition. There are two fractions of S in the soil: carbon bonded sulphur and non-carbon bonded sulphur. The carbon:nitrogen:sulphur (C:N:S) ratio is in the order of 125:10:1.2. The organic fraction becomes available to plants through mineralisation by microorganisms. In plant material a N:S ratio of greater than 17:1 indicates possible S deficiencies, whilst a ratio smaller than 14:1 is indicative of sufficient S. For absorption by the plant roots S must first be oxidised (Ellis, 1998d). This is done through various bacteria as shown in *EQUATION 2.2*

$$\text{Organic material} \longrightarrow H_2S \longrightarrow S \longrightarrow H_2SO_4 \quad (2.2)$$

The oxidisation of S results in the formation of sulfuric acid and thus an increase in soil acidity is observed (Mengel and Kirkby, 1981). Losses in the process of mineralisation can be expected in the leaching of sulfates (SO_4^{2-}) and volitisation of H_2S, especially if mineralisation takes place under anaerobic conditions.

The atmosphere qualifies as a major source of S to the plant. Small amounts of sulphurdioxide (SO_2) have been shown to be absorbed by the leaves of plants.

2.2.6.2 Factors affecting the availability of sulphur

- Soil

In very acid soils a positive charge can develop (through the presence of Al) and present the negatively charged sulfate ions with binding positions for adsorption. In slightly less acid soils (pH 5) there is little potential for adsorption and leaching is a possible result. Generally, adsorption of sulphate (SO_4^{2-}) increases as the soil pH falls and is higher in koalinitic soils than the soils rich in 2:1 clay minerals. Uptake of the sulfate anion (SO_4^{2-}) is not particularly pH sensitive and absorption through the roots occurs over a range of soil pH (Mengel and Kirkby, 1981).

- Soil organic matter

Organic material is an important source of organic S. Under conditions where the ratio between N and S is not optimum, immobilisation of S can take place (Marchner, 1997).

2.2.6.3 Visual symptoms of nutrient stress

As S is common in most soils, deficiencies are not very common. Most of the root absorbed S is easily translocated through the xylem to the shoots. The end product of use determines the mobility of S and thus deficiencies, as chlorosis, can be observed either on the older foliage or a general chlorosis over the whole tree or chlorosis on the younger foliage (more common). This is distinguished from a N deficiency where the older leaves are the first to become chlorotic.

- Conifers

In young trees, Timmer (1991) has described the deficiency as a general chlorosis over the whole plant that may be followed by necrosis in severe cases. The chlorosis in older trees is characterised by needles that are uniformly yellow coloured from base to tip (Schultz, 1997).

- Broadleaves

In expanding leaves the interveinal areas turn pale green and with time worsens to yellowing that spread to the older foliage. Young leaves may become pale red, the leaf tips and the terminal buds may die (Dell, 1996; Dell *et al.*, 1995). Leaves that are uniformly yellow are indistinguishable from those suffering from a N deficiency, apart from the fact that N deficiency first appears on the older leaves (Reuter and Robinson, 1997).

2.2.7 Iron

2.2.7.1 Geochemistry

Apart frooom silicon, iron (Fe) is the most abundant element on the planet. It has the ability to form stable compounds with sulphur (S), oxygen (O) and silicon (Si) and it occurs as the natural metal in meteorites and in the earth's interior. Iron is present in many primary minerals such as hornblende, biotite and chloride. These are decomposed by weathering and other chemical reactions into secondary minerals of oxides and hydroxides (Sauchelli, 1969).

The valence of iron (commonly Fe^{2+} and Fe^{3+}) is indicative of the state of oxidisation in the natural environment. The Fe^{3+}/Fe^{2+} ratio is higher in granitic soils than in basalt because granites originate at higher levels in the soil profile and are usually found at the crest of the landscape (Mortveld *et al.*, 1972). Soils that are inherently low in Fe (e.g. soils derived from sandstones/quartsites) can be expected on siliceous limestone soils (Ellis, 1999).

The geochemistry of Fe is discussed by the general behaviour of Fe in the weathering zone, i.e. in an oxidizing and reducing environment, as a iron silicate and as transported iron.

(i) Iron in an oxidizing environment with atmospheric O_2 being the dominant agent: there are various forms of Fe^{3+} in the soil environment with hematite (Fe_2O_3) being the more stable in comparison to goethite (FeOOH). The oxidisation/reduction reaction is

completely reversible and the state of Fe is determined by the organic content of the soil and the O_2 availability (Mengel and Kirby, 1981).

The most abundant form of Fe in the surface environments is Fe_2O_3. Weathering of Fe^{2+} minerals on an outcrop to form Fe^{3+} minerals is known to be fairly rapid. This leads to higher levels of insoluble Fe_2O_3 and to an increase in acidity (*EQUATION 2.3)*

$$4Fe^{2+} + O_2 + 10H_2O \longrightarrow 4\,Fe(OH)_3 + 8H^+ \quad (2.3)$$

This also forms stable hydroxides (or oxides) in the presence of solutions with pH values as low as 2 or 3. An acid is formed with the oxidisation of sulphur along with Fe (*EQUATION 2.4)* (Mengel and Kirby, 1981)

$$4FeS_2 + 15O_2 + 8H_2O \longrightarrow 2Fe_2O_3 + 8SO_4^{2-} + 16H^+ \quad (2.4)$$

The accumulations of ferris oxides in the strongly acid soil solution in the weathered zones of iron sulphide deposits are well known. In sulfide rich areas (arid or in overlimed areas with a pH>7) Fe^{2+} precipitates as a sulfide and deficiencies of iron is observed or induced.

(ii) Iron in a reducing environment: bacteria use carbon (C) to reduce Fe^{3+} to Fe^{2+} and SO_4^{2-} to S, yielding pyrite (high levels of S^{2-}) or siderite ($FeCO_3$) (low levels of S^{2-}). Iron stays in solution if both CO_3 and S^{2-} are low.

(iii) Iron silicates ($FeSiO_3$): are formed in sedimentary rocks in the form of hydrous silicates (of which glauconite and chamosite are the most common). Iron smectites do occur as weathering products of ferromagnesium phyllosilicates.

(iv) Transported iron: Fe that is transported as fine (particularly hydroxides) or as coatings on grains. The insolubility of Fe_2O_3 limits the movement of iron in water that is exposed to the atmosphere (Mortveld *et al.*, 1991). A lateritic hardpan (ferricrete) is one of the results of iron accumulation in the zone of a fluctuating water table (Soil Classification

Working Group, 1991). It is a massive material that is enriched and cemented by sesquioxides, with Fe being the chief constituent.

2.2.7.2 Factors affecting the availability of iron

- Soil

Iron is contained in most soil types, with the possible exception of some lime- and sandstone soils. Absolute deficiencies of Fe in the soils are thus uncommon, but as such, deficiencies do occur. There is however no correlation between the total amount of Fe in the soil and the amount of iron that is ultimately absorbed, contained and used by a plant. Precipitates (see following section) in the plant itself renders some forms of Fe unusable.

The majority of Fe deficiencies are found on calcareous (thus high pH) soils. The presence of free lime and bicarbonate ions in arid and semi-arid areas lead to induce Fe deficiencies due to the precipitation of iron carbonate. This soil condition is also found in mismanaged and over-limed soils.

Although Fe deficiencies are normally associated with alkaline soils, iron disorders are also found on acid soils. This has been the case in saturated, acid sulphate soils of rice paddies in Thailand. The Fe disorders occur due to the presence (excess) and interactions with other nutrients (Mengel and Kirby, 1981).

- Soil moisture

Soil temperature and soil moisture content affect the availability of Fe by the limited reduction of Fe^{3+} to the more accessible Fe^{2+}. This is found in wet and cold soil conditions with reduced bacterial activity and limited root growth. There is less active ion absorption and higher levels of bicarbonate ions (HCO_3) through an increase of CO_2 solubility in soil water.

- Interaction with other nutrients

1. Phosphorus - iron

On soils with a history of over-fertilisation and the resultant accumulation of these nutrients in the soil water, Fe deficiencies can be induced by a high P concentration.

High soil P levels can decrease the amount of iron in the plant through the immobilisation of soil iron, the inhibition of iron absorbed by plant roots and iron that is transported within the plant the immobilisation of plant Fe (Mortveld *et al.*, 1991).

2. Manganese- iron

The interaction between Fe and Mn results in induced Fe deficiencies being observed in plants growing on Mn rich soils. The relationship is well documented, and although the redox system (*EQUATION 2.5*) has been studied, the precise mechanisms between the elements are still not clearly understood.

$$Mn^{3+} + Fe^{2+} \rightleftharpoons Mn^{2+} + Fe^{3+} \qquad (2.5)$$

Manganese is a stronger reducing agent than Fe, and in the soil the iron is oxidised to the unavailable Fe^{3+} form. Low levels of Fe can also be attributed to the formation of insoluble Mn oxides on the roots. This has been found to be the case on red, acid soils with a high iron and Mn content (like areas in Mpumalanga) (Ellis, 1999).

3. Copper- iron

The uptake of Fe is restricted by a direct Cu antagonism (Mortveld *et al.*, 1991). The resultant effect is an induced Fe deficiency in the young and juvenile parts of the tree.

4. Molybdenum- iron

See section **2.2.12 Molybdenum**.

5. Nitrogen- iron

The form of applied N may affect the availability of soil Fe. Increases in the NO_3-N uptake cause the exudation of HCO_3^- and thus Fe precipitation. The precipitated Fe is unsoluable and not available for plant uptake.

2.2.7.3 Visual symptoms of nutrient stress

Iron in the plant is relatively immobile and thus the younger leaves will be the first indicators of a deficiency, normally colouring to yellow. Interveinal chlorosis of the lamina is indicative of most iron deficiencies.

- Conifers

Symptoms of chlorosis on young needles is a lack of bud development in young seedlings (Timmer, 1991). Yellowing of needles with the base of the needles becoming progressively more yellow is observed in older trees (Schultz, 1997). Deficiencies are not very common. Most of the Fe in a seedling is found in the roots and thus the foliar Fe content of symptomatic seedlings can be higher than the foliar Fe content of healthy seedlings (Will, 1961). Visual determination of deficiencies is thus a better indication of Fe shortages than foliar analyses.

Lime-induced chlorosis is often found in the nursery. Slight chlorosis of the newer foliage is found with minor Fe deficiencies, but in severe cases the whole seedling becomes chlorotic and stunted. It is almost impossible to correct Fe deficiencies in severe cases where the seedlings have turned bright yellow to white (Van den Driessche, 1991).

- Broadleaves

The interveinal areas of the young and expanding leaves are of a pale green colour. In time the chlorosis intensifies and green parts of leaf are limited to the major and minor veins (Dell *et al.*, 1995). Symptoms are always worse in young leaves, but the chlorosis may spread to the older leaves. In severe cases of deficiencies the young leaves may become white and necrosis can follow. At the start of a growing season (during growth flush) there is a marked difference between the older and younger leaves (Dell, 1996).

Copious amounts of Fe fertiliser can result in toxicity. Symptoms take the form of stunted growth coupled with chlorosis or necrosis (Ellis, 1999).

2.2.8 Manganese

2.2.8.1 Geochemistry

Manganese (Mn) is a lithophile element and occurs in both meteorites and in igneous rocks. Many minerals contain Mn. Some of the minerals are: simple oxides like pyrolusite (MnO_2), hausmanite (Mn_3O_4), manganite (MnOOH); complex oxides like braunite ((Mn

$Si)_2O_3$), psilomelane ($MnO_2.xH_2O$ +Ba, K, etc.); carbonite minerals like rhodochrosite ($MnCO_3$) and silicate minerals like rhodonite ($MnSiO_3$) (mengel and Kirby, 1981).

The chemistry and geology to Fe is remarkably similar, but Mn shows three naturally occurring valences (Mn^{2+}, Mn^{3+}, Mn^{4+}) to the two of iron. The trivalent ion is unstable and not very common. In reducing environments the stable Mn^{2+} compound is found and in oxidizing conditions the dioxide, MnO_2 (Mn^{4+}) is the stable form of Mn (Marschner, 1997).

In igneous rocks Mn is more common in basalt than in granite. In sedimentary rocks manganese is more abundant in limestone and dolomite that in shale. The heavy metal ions of Mn are thus less strongly adsorbed to the finely grained sediments of the soil particles.

Weathering of Mn containing silicates or carbonates under reducing conditions results in Mn^{2+} in solution. Compounds that are formed are similar to Fe, but they are more soluble and no stable sulfide minerals are formed.

The chemistry becomes more complicated under oxidizing conditions in that any one of a large number of Mn compounds may be formed. The most stable product of complete oxidation is pyrolusite (MnO_2). This form of manganese (Mn^{4+}) is the least likely to be absorbed by plants. Transport of higher oxides (Mn^{3+}, Mn^{4+}), through increased insolubility can pose serious problems, but because oxidized compounds can be reduced to Mn^{2+}, mobility is increased. The higher oxides can also form stable organic complexes as a transport mechanism. There is a continuous change of Mn between the oxidized and reduced forms.

As the level of Mn^{2+} depends on oxidation-reduction reactions, the availability of Mn is influenced by factors that control these reactions. The most important factors are soil pH, organic matter content, soil moisture content and microbial activity (Mengel and Kirby, 1981).

There is a large variation in the amount of Mn in the soil. The lowest levels are found in sandstone derived soils (10 – 100 ppm) and overall levels in the soil can be expected to vary between 10 and 3000 ppm (Mortveld *et al.*, 1982).

2.2.8.2 Factors affecting the availability of manganese

- Soil

The availability of manganese decreases with an increase in pH. The probable cause is favourable conditions for microbial activity and hence oxidization to the insoluble Mn^{4+} forms. Liming of an organic rich soil can induce Mn deficiencies. Sterilization of soil thus results in an increase in Mn availability by the reduction of microbial activity.

- Soil water

Deficiencies of Mn are commonly found in organic or mineral soils that are poorly drained (Mortveld *et al.*, 1972). In soils that fluctuate between over-saturation and drought, deficiencies can occur. During wet conditions manganese is reduced to the highly mobile Mn^{2+} and leached from the profile. During drought periods the Mn may be oxidized to the stable forms (Mn^{4+}).

- Interaction with other nutrients

1. Iron - manganese
   See section **2.2.7 Iron**.

2. Magnesium – manganese
   See section **2.2.5 Magnesium**.

2.2.8.3 Visual symptoms of nutrient stress

Manganese is rather immobile in the plant and thus deficiency symptoms are first visible on the young growth.

- Conifers

In *P. taeda* there are more single needle fasicle sheaths than the normal three needles per sheath (Schultz, 1997). Needles are chlorotic and in some cases this accelerates to necrosis (Timmer, 1991). In Mn deficient stands of *P. radiata* the needles are short with yellow and dead tips, and limited needle retention on the tree (Turvey *et al.*, 1992).

- Broadleaves

The margins of young leaves become pale green and withered. Chlorosis extends between the lateral veins towards the midrib. The major veins are always surrounded by green tissue. Because of limited mobility, the terminal meristems can die in severe deficiency cases (Dell *et al.*, 1995; Dell, 1996).

High soil concentrations of Mn (such as in Mpumalanga) result in interaction with Fe. The redox reaction causes immobility of iron (Fe^{3+}) and thus Mn toxicity is manifested as an Fe deficiency. If a toxic nutrient interacts with the metabolism of a second nutrient, it can also result in visual symptoms of deficiency and visual symptoms of toxicity. On acidic soils it has been found that excessive levels of soluble Mn can induce Fe deficiencies in younger foliage and Mn toxicity symptoms on the older foliage (Reuter and Robinson, 1997).

The most noted effect of Mn toxicity is seen by Marschner (1997) as the antagonism with Mg. Cases have been observed in Mpumalanga where pine trees that are growing on dolomite lithology (with high soil Mg and Mn values) are prone to symptomatic Mg deficiencies (Schutz, 1989).

2.2.9 Boron

2.2.9.1 Geochemistry

Boron is a strictly lithophile (occurs dominantly in silicate minerals) element and always occur in combination (three or four fold) with oxygen. It is a light non-metal with a constant valence of B^{3+} and it has a very small ionic radius.

The borosilicates (tourmaline and axinite) and anhydrous borates (ludwigtite, Mg_2FeBO_5; kotoite, $Mg_3(BO_3)_2$ are high temperature minerals and hydrous borates (borax, $Na_2B_4O_7.10H_2O$; kernite, $Na_2B_4O_7.4H_2O$; colemanite, $CaB_6O_{11}.5H_2O$; ulexite $NaCaB_5O_9.8H_2O$) are low temperature minerals (Mengel and Kirby, 1981).

Borates are reasonably soluble and thus they readily accumulate in sites of evaporation. These solutions mostly contain H_3BO_3 (weak acid) and $H_2BO_3^-$, with tetraborate ($B_4O_7^{2-}$) only found in concentrated solutions.

In igneous rocks the concentration of B is greater in granitic rocks than in basalt. The influence of temperature in the formation of high temperature B minerals causes the concentration of B to be high in dikes and metamorphic rocks. A higher B concentration is found in mica than in volcanic rock than in plutonic rock. Tourmaline is a mineral that is found in igneous rocks, like the Cape granites, but B in this form is not readily available for plant growth. The non-ionic nature of B allows it to be rapidly leached from the soil. Coarse textured soils are vulnerable to leaching and may contain low amounts of B. Soils that are rich in aluminium oxides tend to have reduced amounts of plant available B (Bingham *et al.*, 1971).

The highest concentration of B is found in sea water (4.6 ppm) and the subsequent evaporation from the ocean surface as a B-rich vapour allows for adequate amounts of B that is precipitated on or near coastal areas. This form of precipitation and the weathering of B containing minerals are the main sources of B into sedimentary rocks. The B content of sedimentary rocks is thus much higher than the average concentration found in igneous rocks, with shales showing the highest average (100 ppm). Highly leached acid soils are low in available B (Sauchelli, 1969). Soils derived from granite and other igneous rocks are low in B content.

The mining of B fertilisers is mostly done in areas of accumulation of hydrous borate minerals formed by the evaporation of salt lakes (borates of Na or Ca) or sea water (borates of Mg). Boron is further associated with micas, clay and sesquoxides in the soil and particularly in sedimentary rocks.

2.2.9.2 Factors affecting the availability of boron

- Soil

The retention of B in the soil is pH dependent with the maximum adsorption in the pH range between 7-9. The neutral species H_3BO_3 is commonly expected in the soil, but at pH 9 and above, the $H_2BO_3^-$ species is predominant. This condition of soil pH is however seldom encountered and most deficiencies occur after over-liming of a soil or on a naturally calcareous soil. In contrast to the anions of P and Mo, adsorption of B increases with increasing soil pH (Mengel and Kirkby, 1981).

- Soil water

Seasonal B deficiencies have been encountered with conditions of moisture stress. This can be attributed to a reduction in the mineralisation tempo and thus the amount of B being set free from organic material.

Complex interaction between K ions (involved in water status regulation) and the B ions can result in an induced B deficiency. Because B is passively absorbed by the root system, it is dependent on the rate of sap flow and thus transpiration, for being taken up by the plant. Under water stress conditions there is thus limited B uptake.

- Soil organic matter

B that is adsorbed to organic matter is not readily available for plant uptake, but through mineralisation it becomes an important source for plant nutrition. There is a correlation between soil organic content and hot water soluble B, but reports that soil organic matter influences the availability of B to plants has not been proven (Gupta, 1968; Mortveld *et al.*, 1991).

- Interactions with other nutrients

1. Calcium – boron

In agricultural crops a B deficiency can be determined by the Ca:B ratio. If this ratio is low at high soil Ca content, little B is available to the plant because of the formation of

less soluble calciumborates (Mortveld *et al.*, 1972). In contrast to this a decrease in boron uptake has been found to be in response to increased pH rather than Ca or Mg soil content (Gupta and MacLeod, 1977).

2.2.9.3 Visual symptoms of nutrient stress

There are many physiological symptoms related to B deficiencies of which tip-dieback is the most renowned. In colder, frost prone areas this symptom has been attributed to frost damage, but studies on pines in Europe provided evidence that B deficiencies (tip dieback and growth disturbances) had been incorrectly diagnosed as frost dieback (Moller, 1983; Veijalanen, 1983). There are also indication of increased frost resistance through B fertilisation, but there is still uncertainty whether B deficiencies are being accentuated by low temperature stress (Shorrocks, 1997).

Studies by Snowdon (1982; 1983) have indicated that the uptake of B by pine trees may be genetically fixed. The sporadic occurrences of deficiency symptoms in *P. radiata* stands seem to confirm this.

- Conifers

In the younger trees tip dieback and chlorotic-to-necrotic foliage is observed late in the growing season. The dieback of the growing point leads to characteristic crooking of the leading shoot (Timmer, 1991). Resin exudes from the buds and/or needles (Schultz, 1997). The sequential symptoms of a B deficiency starts with the yellowing of young needle tips, production of resin droplets, then needle chlorosis and leader dieback with repeated dieback resulting in multiple leaders, lack of apical dominance and a tree with a bushy appearance (Snowdon, 1982; Hopmans and Clerehan, 1991; Lambert *et al.*, 1997). In some cases the pith is black or dark brown (Reuter and Robinson, 1997). Dead shoots are about 25 cm long and twisted in an 'inverted hockey stick' and the occurrence is strongly seasonal (Will, 1978; Snowdon, 1982; Will, 1985).

- Broadleaves

In the young leaves there are slight pigmentation changes as chlorosis or purple tinges. The growth and the development of the growing tips are adversely affected with developing leaves that are malformed. Leaf rolling and weeping branches can occur. The prostrate effect of the branches is the result of reduced wood lignification. In some species the upper nodes are elongated and through continuous dieback of shoot tip there are a multitude of live and dead shoots. The older leaves may abscise early and bark may show signs of bleeding (Dell, 1996; Dell *et al.*, 1995).

There is a narrow margin between sufficiency and toxicity of B but species vary in the degree of tolerance to high levels of B. In South Africa toxicity will mostly be caused by over fertilisation of B fertilisers, whilst in other countries sources of toxicity is from irrigation waste (Nambiar, 1984). In young pine seedlings the foliage becomes glaucous, growth is stunted and in extreme cases mortality occurs. The ratio of toxic to adequate B levels is the smallest for any nutrient element and therefore correct application is very important.

2.2.10 Copper

2.2.10.1 Geochemistry

The forms of copper (Cu) that are found in rocks are mostly the stable and abundant sulfide minerals (thus chalcophile in behaviour) rather than the silicates or oxides. As a sulfide the commonest mineral is the complex sulfide chalcopyrite ($CuFeS_2$), but more simple sulfides like chalcolite (Cu_2S) and covellite (CuS) are also found. Copper minerals of oxides (like cuprite (Cu_2O) and tenorite (CuO)) and silicates (like chrysocolia ($CuSiO_3.2H_2O$)) do occur, but because of its strong covalent bonding, substitution in silicate structures are limited. Of the best known minerals, the carbonate copper mineral, malachite ($Cu_2(OH)_2CO_3$), is collected for its brilliant green and blue surface colours (Mortveld *et al.*, 1972).

Valences of copper vary from Cu^{1+} to Cu^{2+} and Cu^{3+} but in the soil the divalent form almost exclusively dominates. The concentration of Cu in the soil varies between 10 – 80 ppm (Mengel and Kirby, 1982).

In igneous rocks there is a large difference between the abundance between basalt and granite. Copper is heavily concentrated in basalt rather than granite, the reason being that sulfides and ferromagnesium silicates are found in basalt. In the weathering of ferromagnesium minerals (like biotite, hornblende and olivine), Cu is substituted (Cu^{2+} for Ca^{2+}, Fe^{2+} and Mg^{2+}) and released into the soil solution as Cu^{2+} or $CuOH^{+}$ (Mortveld *et al.*, 1991; Ellis, 1999b).

The marked concentration of Cu in sandstone has been ascribed to the Cu being adsorbed as ions to the surface of fine grained particles. The sulfide mineral chalcopyrite ($CuFeS_2$) is commonly found in sedimentary rocks.

The tendency of Cu to form strong covalent bonds causes it to be strongly adsorbed to surfaces available in the soil. Most of the copper in the soil is held on organic and inorganic colloids such as ferric hydroxide ($FeOH_3$) and organic matter (in peat soils). Adsorption may be strong enough to keep the concentration of copper (mostly as Cu^{2+}) in the soil solution low, and it has been shown that copper forms stable complexes with fulvic acids. Copper is considered to be one of the more mobile heavy metals in the surface environments (Mortveld *et al.*, 1972) but leaching of Cu is however unlikely.

2.2.10.2 Factors affecting the availability of copper

- Soil

The solubility of Cu decreases as the alkalinity of a soil increases. This is the case in overlimed soils or in soils that are naturally rich in lime (Mortveld *et al.*, 1972). Acid sandy soils (podzols in particular) are also prone to deficiencies. Areas along the Cape coast and in Zululand exhibits shortages of Cu (Ellis, 1999b). The shortages on very acid soils can also be the result of aluminium-copper antagonisms.

- Soil organic matter

Deficiencies of Cu on peat soils are common. This may be the result of absolute deficiencies or by the formation of stable bonds with the organic fraction.

- Interaction with other nutrients

1. Phosphorus - copper

Heavy fertilisation of phosphates may induce a Cu deficiency in areas with a low Cu soil content.

2. Iron - copper

See section **2.2.7 Iron**.

2.2.10.3 Visual symptoms of nutrient stress

Symptoms of Cu deficiency occur in meristematic areas which is an indication of phloem immobility (Dell, 1996). Classic examples of Cu deficiencies were observed in New Zealand (Will, 1985).

- Conifers

Needles with tan or greenish-yellow bands are symptomatic of copper deficiency (Schultz, 1997). Needles may be 'tip-burned', twisted and in severe cases the young shoots are twisted or bent (Will, 1985; Timmer, 1991). Symptoms originate on young foliage followed by necrosis (Reuter and Robinson, 1997). Needles are spirally twisted and droop at the end of the seedling. The tips are of a yellow or bronze colour (Will, 1961).

- Broadleaves

Loss of leaf lustre, expanding leaves with undulating or deformed margins, interveinal chlorosis, stem bleeding at nodes and reduced wood lignification is symptomatic of the first stages of deficiency. In the later stages necrosis of leaves, large internodes and the death of lateral buds and the shoot apex occur (Dell, 1996).

Copper toxicity generally result in chlorosis of the leaves (due to an iron antagonism) and stunting of growth. Toxicity is first encountered in the root tips and then when the formation of lateral roots is depressed (Hale and Orcut, 1987).

2.2.11 Zinc

2.2.11.1 Geochemistry

Zinc occurs mainly as the single sulfide mineral sphalerite (ZnS) and is mainly chalcophile in behaviour. The zinc ion (Zn^{2+}) occurs as this valence in natural materials. Because of its similar size to Fe^{2+} and Mg^{2+}, it may replace these ions through isomorphous substitution in some mineral structures. Most of the zinc in the soil solution originates from ferro-magnesium minerals like augite, hornblende and biotite (Mengel and Kirby, 1981).

The most common sulfide mineral of zinc is sphalerite (ZnS). Other minerals are the carbonate minerals, smithsonite ($ZnCO_3$), and as the silicate mineral hemimorphite ($Zn_4(OH)_2Si_2O_7.H_2O$) (Mortveld *et al.*, 1978).

Many zinc salts are also formed in the soil (e.g. zincite (ZnO)), but because of their solubility they do not persist under wet conditions. The level of zinc in the soil solution is low and they are absorbed onto the clay minerals, hydrous oxides and organic matter fractions as the Zn^{2+} ion. Under reducing circumstances any sulphates that are present in the soil can be reduced to sulfide and can cause the precipitation of zinc as ZnS.

Soils derived from basic igneous rock are high in Zn. The Zn content of a soil is largely dependent on the parent material. Amongst sedimentary rocks the highest concentration is found in shales (130 ppm). The Zn content on sandstone is low (20 ppm) but not as low as in soil from siliceous parent material (10 ppm) (Mengel and Kirby, 1982). On acid leached sandy soils of the western and southern Cape and the Zululand sands (Ellis, 1999a), the natural content of Zn is low and deficiencies can be expected. The probability is that Zn found on these soils will be leached out. Soils that are derived from acid rocks (with coarse textures) tend to be low in Zn content.

Zinc forms complexes with soil organic matter that are soluble when they are associated with amino-, organic- or fulvic acids, but insoluble organic complexes are formed in the presence of humic acids (Mortveld *et al.*, 1978). Evidence suggests that although zinc is distributed throughout the soil profile, it tends to accumulate in the top horizons. Removal of the topsoil through silvicultural practices (like scalping) can increase the likelihood of a Zn deficiency (Moraghan and Mascagni, 1991).

2.2.11.2 Factors affecting the availability of zinc

- Soil

As with most other micronutrients, the availability of Zn decreases with an increase in the soil pH. This is found when enough carbonate or hydroxides are present to form precipitates like smithsonite ($ZnCO_3$).

- Interaction with other nutrients

1. Phosphorus - zinc

Fertilisation of P quite commonly induces Zn deficiencies. This may be because of the forming of insoluble zinc-phosphate that is not available for plant uptake or because Zn translocation in the plant is depressed by P.

2. Nitrogen - zinc

As N fertilisation increases the growth of plants, a Zn deficiency may be induced. The nature of this deficiency sprouts from marginal Zn availability that cannot comply with a greater growth rate and that leads to a dilution effect (Marschner, 1997).

2.2.11.3 Visual symptoms of nutrient stress

Zinc deficiencies occur in the whole plant and this suggests that Zn is somewhat mobile. Young foliage may however be singularly severely affected.

- Conifers

Needles are short, thick and twisted and yellow of colour (Schutz, 1997). Older needles are shed early and this leads to tufting (Timmer, 1991). Extreme stunting of trees (in severe cases the trees are rosetted with top dieback), and multiple leaders cause stem malformation (Will, 1985). Deformation and chlorosis of the first apical primary leaves were the first symptoms observed by McGrath and Robson (1984) in some pine species.

- Broadleaves

Zinc deficient trees are stunted and the leaves are small and crowded (Dell *et al.*, 1995). In the early stages the expanding and recently mature leaves turn bluish green and the leaf margins turn pale yellow. In more severe stages the deficiency spreads to older leaves, causing shorter internodes and smaller leaves which give the tree a stunted appearance (Dell, 1996).

Toxic amounts of zinc in natural soils are not very common and are usually the result of mining or sewage affluent (Motrveld *et al.*, 1972; Ellis, 1999a). Zinc toxicity may resemble a deficiency and can be rectified by liming or the addition of Mo.

2.2.12 Molybdenum

2.2.12.1 Geochemistry

Molybdenum (Mo) is a geochemically curious element as it differs from the elements that are close to it on the periodic table (Mortveld *et al.*, 1972). Molybdenum occurs mainly as a stable sulfide, molybdenite (MoS_2), and is more related to the chalcophile elements (sulfides) than its lithophile (e.g. occurs dominantly in silicate minerals) periodic table neighbours. The small size of Mo^{6+} with its high charge and tendency to form covalent bonds, ensures that this element occur mostly as oxy-anions.

As an oxide it occurs as the scarce ilsemanite mineral ($Mo_3O_8.8H_2O$) with a valence of $Mo^{6+}(MoO_4^{2-})$. The Mo^{4+} valence is mostly limited to the common molybdenite mineral (sulfide salt) (Salisbury and Ross, 1985). In near-surface environments Mo reacts as an

anion (MoO_4^{2-}) in the mostly insoluble forms of wulfinite (Pb MoO_4), powelite (Ca MoO_4) and ferrimolybdenite ($Fe(MoO_4)_3.8H_2O$.

In igneous rocks the average Mo content is 1 to 2 ppm with the greatest concentration of molybdenum in biotite minerals with the greater proportion of the metal contained in the more abundant feldspars. The Mo^{4+} valence can also be responsible for limited substitution of Ti^{3+}, Fe^{3+} and Al^{3+} in silicate structures. In sedimentary rocks there is a higher concentration of Mo (as MoO_4^{2-}) in shale than in sandstone or limestone. In Australia Mo deficiencies occur in crops growing on soils derived from sedimentary rock, basalt and granite (Moraghan and Mascagni, 1991).

The weathering of Mo minerals in different pH solutions results in the following molybdate ions:

- MoO_4^{2-} at pH (H_2O) values > 5 or 6
- $HMoO_4^{1-}$ at pH (H_2O) values < 5

These ionic species tend to precipitate in the presence of Ca^{2+}, Pb^{2+}, Cu^{2+} or Fe^{2+} with the most common ferrimolybdenite, showing the least solubility at pH (H_2O) ranging from 2.7 to 4. In an alkaline solution the Fe compounds decompose with the resultant dissolution of the Mo and $Fe(OH)_3$ groups (Gupta, 1997) :

$$Fe_2(MoO_4)_3 + 6OH^- \longrightarrow 2Fe(OH)_3 + 3MoO_4^{2-} \qquad (2.6)$$

In soil the Mo anion is adsorbed on positively charged colloidal particles and is readily adsorbed by $Fe(OH)_3$ (ferrihydroxide) at low pH values. At higher pH values the anions are not bound and thus the plant availability of Mo is higher in more alkaline soil. Deficiencies of this element thus occur on soils of low to very low pH and with a high Fe_2O_3 content as found on the leached acid soils of the North Eastern Cape, Natal Midlands and Mpumalanga.

2.2.12.2 Factors affecting the availability of molybdenum

- Soil

In low pH soils the Mo anion is adsorbed onto Fe complexes (reverse of *EQUATION 2.6)* with the resultant formation of ferrimolibdenite. In time this form of Mo becomes less available for plant uptake, and deficiencies can be induced. Aluminium in the soil does not adversely affect the availability of Mo because aluminiummolibdenite is relatively soluble in the soil (Gupta, 1997).

Soil pH is the most important factor affecting the uptake of Mo (Gupta, 1997). The highest amount of Mo is found in soils derived from limestone and shale. Increases in Mo availability to plants are thus engineered by raising the pH of a soil.

- Interaction with other nutrients

1. Sulphur - molybdenum

There is a strong antagonistic relationship between the Mo and S ions. This is caused by the direct competition for uptake by the two divalent ions of similar size and configuration (Mortveld *et al.*, 1972). Fertilisers that contain sulphur should carefully be applied in areas that are low in Mo content or where deficiencies occur.

2. Phosphorus - molybdenum

The positive relationship between P and Mo is a result of improved uptake and translocation of Mo in and by the plant. In the soil, the adsorbed Mo is replaced by P and thus becomes available for uptake in the soil solution (Mortveld *et al*, 1972). The general positive effect that P has on the growth of plants (particularly the root system), also allows for a greater soil volume that a plant may forage in, and so increases the absorption of various nutrients.

3. Iron - molybdenum

There are conflicting views concerning the relationship between Fe and Mo. Molybdenum results in Fe chlorosis (thus an induced deficiency) in some plants, but in other plants an increase in Mo results in higher concentrations of Fe in the plants (Mortveld *et al.*, 1972). Molybdenum has a positive effect on the accumulation of Fe through enhanced Fe uptake. Plants deficient in Mo showed the least uptake of Fe (Mortveld *et al.*, 1972).

4. Copper - molybdenum

The antagonism between these nutrients is of such a magnitude that toxicity and excesses of either are alleviated by the application of the other. This antagonism is founded in the disruption of each of the nutrient's metabolic functions by the presence of the other nutrient. This antagonism is widely known in the field of animal nutrition (Mortveld *et al.*, 1972).

5. Nitrogen – molybdenum

Molybdenum is essential to the assimilation and use of N in the plant. Without Mo a plant experiences N deficiencies (Kabata-Pendis and Pendias, 1985). Plants that receive NO_3-N are more likely to experience Mo deficiencies as NO_3-N has to be reduced (by the Mo-containing nitrate reductase enzyme) to NH_4-N for assimilation into proteins (Gupta, 1997). The uptake of Mo from the soil is greater when the plant uses more NO_3-N than NH_4-N.

2.2.12.3 Visual symptoms of nutrient stress

Deficiency symptoms have not yet been clearly defined. As a nutrient needed in minute amounts, the study of Mo has been very limited and deficiencies in the field seldom recorded.

- Conifers

Chlorosis of leaves is followed by necrosis of tissue, beginning at the tip of the needle and eventually covering the whole leaf (Timmer, 1991; Mortveld *et al*, 1972). On older trees the symptoms can be similar to a N deficiency due to the disruption of N nutrition.

- Broadleaves

Symptoms often consist of an interveinal chlorosis occurring first on the older or mid-stem leaves, then progressing to the youngest leaves. Most *Brassicaceae* spp. show symptoms of a deficiency that is described as 'whiptail' disease. In some of these cases the leaves do not become chlorotic but develop severely twisted young leaves, which eventually die (Salisbury and Ross, 1992). Because Mo is actively involved in the N

reduction in the plant, some of Mo deficiencies can take on the characteristics of a N deficiency.

Stunted growth and necrotic leaf points are the most common visual deficiency symptoms of toxicity. The Mo content of plants can be relatively high before toxicity occurs. Due to the interaction (and antagonisms) with other nutrients (like Cu), toxicity can be alleviated.

2.3 The function of nutrients

This section summarises the physiological roles of various nutrients in a plant or tree.

2.3.1 Nitrogen

- Seventy percent of nitrogen is found in chloroplasts
- Most nitrogen is used in the formation of proteins
- Constituent of amino acids, nucleic acids, nucleotides

2.3.2 Phosphorus

- Energy metabolism – essential part of sugar phosphates that are involved in photosynthesis, respiration, etc. Incorporated into ATP (adenosine triphoshate)
- Structural integrity of membranes (phospholipids) is enhanced through P
- Integral form of storage (phytic acid is storage form)
- Part of nucleotides (RNA and DNA)
- Phosphate spectacularly promotes the absorption of molybdate

2.3.3 Potassium

- Activator of enzymes essential for photosynthesis and respiration
- Activates enzymes needed to form starch and proteins
- Influences osmotic potential and thus turgor pressure regulator
- Promotes the translocation of photosynthate
- Translocation and energy relations
- Regulation of cellur pH
- Balances cation-anion charges

2.3.4 Calcium

- Binds pectate polysaccharides that forms part of the middle lamella in the cell plate
- Needed to form microtubules, mitichondria and chloroplasts
- Essential for normal membrane functions
- Cofactors of various enzymes
- Detoxification of other ions
- Needed in areas of growth (roots and shoots)
- Roothairs do not develop on roots with the absence of Ca
- Balances cellular cation-anion charges

2.3.5 Magnesium

- Central atom of the chlorophyll molecule
- Combines with ATP and affects the functioning thereof
- Activates many enzymes needed in photosynthesis and respiration
- Needed for the formation of DNA and RNA
- Essential for phosphate uptake and transfer
- CO_2 assimilation and carbohydrate partitioning
- Regulation of cellular pH

2.3.6 Sulphur

- Constituent of the amino acids cysteine and methiodine that forms proteins
- Constituents of vitamins and coenzymes
- Activates some enzymes
- Part of volatile compounds
- Stimulates the production of oils in plants
- Energy transfer

2.3.7 Iron

- Participates in the formation of chlorophyll
- Forms part of certain enzymes
- Forms part of certain proteins
- Electron transport (hemes) through oxidation-reduction

2.3.8 Manganese

- Structural role in chloroplast membranes
- Responsible for the photosynthetic split of H_2O
- Activate various enzymes
- Role in various metabolic sequences
- Substitute for magnesium
- Oxidation-reduction and energy transfer

2.3.9 Boron

- Elongation of pollen tubes
- Cell division in the shoot apex
- Cell wall biosynthesis and structure
- Participates in the synthesis of RNA and DNA
- Controls the elongation of root tips
- Translocations of sugars from the leaves
- Regulatory role in carbohydrate metabolism

2.3.10 Copper

- Part of several enzymes and proteins involved in redox reactions
- Lignin synthesis
- Pollen formation and fertilisation

2.3.11 Zinc

- Part of enzymes
- Connection with growth regulators (auxin)
- Membrane integrity

2.3.12 Molybdenum

- Part of the enzyme nitrate reductase that reduces nitrate ions to nitrite ions
- Nitrogen fixation in the plant

2.4 Nutrient cycling

The cyclic occurrence of sub-optimal growing conditions necessitates knowledge of nutrient cycles in the forest environment. In many cases seasonal poor growth is the result of adverse environmental conditions that in turn cause nutrient imbalances in the tree. These imbalances may occur over any length of time and usually occur at a time when the tree is physiologically stressed.

A tree utilizes nutrients that accumulate in the forest ecosystem from a complex array of interacting processes and a diversity of nutrient pools. Nutrient cycling conserves these nutrients within the ecosystem through physical, chemical, biochemical and biological processes. Throughout the cycle, plant nutrients may be found in solid, liquid or gaseous phases (Attiwell and Leeper, 1967; Binkley, 1986; Morris, 1986; De Ronde, 1992).

A simplified model (*FIGURE 2.4*) of nutrient cycling contains nutrient pools of the plants, soil and litter. Inputs are from the atmosphere (wet and dry deposition) and the weathering of rocks; and losses (output) through leaching, surface flow and cultural activities (such as harvesting).

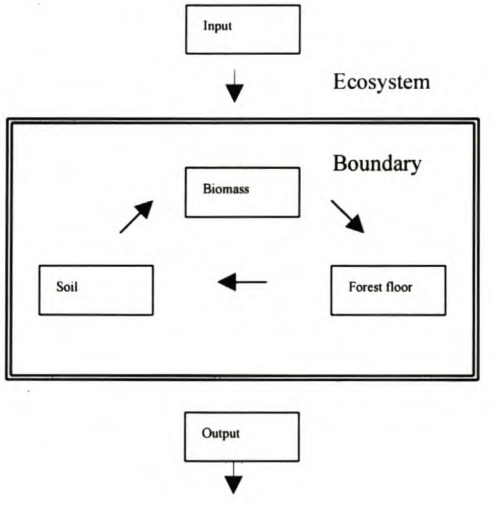


Figure 2.4. *A simplified illustration of the nutrient cycle in terrestrial ecosystems (Morris, 1986)*

The largest nutrient pool is normally the soil that releases nutrients from the weathering of minerals or from decomposition of residual organic matter. For a better understanding of the biomass pool, as seen from a forestry perspective, it can be subdivided into components of foliage, branches, stem and bark (Attiwell and Leeper, 1967; Morris, 1986). Both the amounts of nutrients in the various tree components and nutrient transfer rates change with tree size, tree age and environmental conditions (Wells and Metz, 1963; Schultz, 1997). Although the processes of nutrient cycling are basically the same, the cycling of each nutrient within the tree is unique in terms of quantity and transfer rate. Due to the complexity of this subject, nutrient cycling is only discussed insofar it influences the measurement and determination of nutrient stress in the tree and possible reasons for the occurrence of nutrient imbalances. Foliage is the tissue that is most involved in the recycling of nutrients (Schultz, 1997; Miller, 1984) and thus more attention is given to the recycling process within the tree.

The dynamic nature of nutrients could be seen as problematic in the determination of nutrient availability of a specific nutrient at a specific point in time e.g. soil samples (De Ronde, 1992). For the inference of nutrient status it is needed to understand the interactions between the trees and the growing areas (soils), where and when accumulations of nutrients occur and when certain tree tissues are prone to nutrient depletion. Nutrient ions are taken up by the tree and may be translocated into and out of various tissues where it can either be used in a variety of growth processes or be stored. Nutrients are fated to being immobilized in accumulating structural tissue, or released through litter fall, root death or crown leaching. Retranslocation of nutrients occur mostly before foliage fall when tissue senesce or during the formation of heartwood (Miller, 1986; Schultz, 1997). Through a system of nutrient budgeting, the nutrients that are impossible or unnecessary to conserve are released for accumulation in the soil organic layers where they function as a reserve source. All other nutrients are withdrawn back into the living tissue before senescence. The relative rate of nutrient movement in the forest floor has been found to be: K >> B > Mn > (P, Mg, Ca) > (Zn, Cu) > (N, organic material) (De Ronde, 1992).

Nutrients move continuously in actively growing trees. Large portions of N, P and K in conifers are translocated throughout the tree while much of the Ca, Mg and S is immobilized in the tree's woody parts. In a twenty year old *P. taeda* stand, most of Ca

had to come from sources outside the trees and 60% of the P and 22% of the K were recycled (Wells and Metz, 1963; Schultz, 1997).

The cycles of nutrients within the plantation ecosystem vary not only between different species and growing conditions, but the rates of uptake, accumulation and release in litterfall of a nutrient are largely functions of growth rate (Miller, 1984). As in the growth rate of a stand varies with age, the rates of nutrient cycling may be different at different stages in the rotation. When a young tree grows, it enters a period of a few years where its size increases rapidly with an accompanying increase of foliage that is proportionally high in nutrients. Most of the nutrients are taken up from the soil and only a small proportion is recycled. Only after a substantial canopy has been formed and maintained can recycling of nutrients reach a steady state and peak (Lewis and Ferguson, 1993). In older trees the rates of recycling are not very different from uptake. These patterns in nutrient cycling have led to the description of three nutritional stages in the life of a plantation by Miller (1984) with a fourth being added by De Ronde (1992):

Stage I: Prior to canopy closure when growth is dependent on nutrient uptake. This is the stage where response to fertiliser application common.
Stage II: After canopy closure. Nutrient cycles are developed and there is a reduction in the rate of nutrient accumulation and a better retention of atmospheric nutrients.
Stage III: Late in the rotation. Maturing of the nutrient cycles leads to the immobilization of N in the humus layers and late rotation N-deficiencies can be observed. In the South African context De Ronde (1992) sees P-deficiencies as a greater threat at this stage and further ascribes decreased growth to an increase in physical growth limitation (moisture stress or restriction of effective rooting depth).
Stage IV: This stage includes clearfelling and slash treatment effects.

A study by Miller (1984) compared the nutrient movement between old and young pine trees (*TABLE 2.2*). The transfer of all nutrients in the young 10-year old stand (Stage I) is largest from the uptake portion and the internal recycling is much less. In the older stand (Stage II) the retranslocation within the tree is the larger portion for all nutrients except, Mg.

Table 2.2. *Comparison of transfer and accumulation rates of nutrients modelled for a 10-year old, 2 m tall stand and a 40-year old, 11 m tall stand of* Pinus nigra *var.* maritima *(Summarized from Miller, 1984).*

Transfer	Nutrients (kg/ha/yr)							
	10-year old stand				40-year old stand			
	N	P	K	Mg	N	P	K	Mg
Release from trees	10	1.0	4	2.2	51	3.9	17	7.2
Tree uptake	55	5.5	22	6.3	69	6.0	28	10.9
Retranslocation within tree	11	1.2	7	0.6	69	8.1	38	3.1

Translocation rates of nutrients are the largest in the foliage with 60% to 85% of the nutrients being conserved in this way (Miller, 1984; Schultz, 1997). The period just before abscission sees an increase in movement of nutrients back into living tissue. From *TABLE 2.3* it can be seen that most of the macronutrients are cycled in this way, but that Ca accumulates in the forest litter. Various studies (Miller, 1984; Schultz, 1997) have found that Ca, Cr, Fe, Zn, Cu and Pb accumulate in the litter layer and that N, P and K are recovered into living tissue. During needle fall (late autumn to early winter) of *P. taeda,* Schultz (1997) reported the lowest N and P concentrations of needles that fall but the highest concentrations of Ca and Mg in those needles.

Table 2.3. *The comparison of concentration and amounts of nutrients in young foliage, in the oldest whorl of needles held on a 3-year old tree and newly fallen needle litter in a* Pinus nigra *var.* maritima *stand (Miller, 1984).*

Plant part	Nutrient				
	N	P	K	Ca	Mg
	% Dry weight				
First year needles	1.54	0.15	0.73	0.23	0.11
Old needles	1.25	0.12	0.63	0.45	0.10
Needle litter	0.76	0.07	0.17	0.49	0.08
	mg per 100 needles				
First year needles	67	6	31	10	5
Old needles	53	5	26	18	4
Needle litter	22	2	5	14	2
Proportion of nutrients retranslocated between year one and abscission	0.67	0.67	0.84	-	0.60

The distribution of nutrients in the above ground biomass of commercial tree species and the subsequent loss during and after harvesting (Stage IV) has a marked effect on soil fertility (Anon, 1990). When a plantation is harvested, the forest ecosystem becomes temporarily non-conservative of plant nutrients through the removal of above ground biomass and the increase in drainage and streamflow.

Herbert and Robertson (1991) investigated the rate of nutrient depletion in soils through timber harvesting. The nutrient status of various tree species and their management techniques (e.g. debarking in field versus at the sawmill) vary greatly and they recommend further research into nutrient interaction with cultural systems of forest management. They have found that K is the element most likely to become deficient as a consequence of timber harvesting. This phenomenon has been described by Morris (1983) who found decreases in productivity of second and third rotation *P. patula* tree crops in Swaziland. The trees that were grown on soils derived from parent material that is inherently low in K content (gabbro), were poorer in comparison to sites with soils derived from granite parent material that contain more K. Further studies by Morris (1987) found that the nutrient depletion by the removal of forest biomass was larger than the inherent supply capacity P from igneous resources and K from non-exchangeable reserves. A decline of Ca was observed under a eucalypt plantation (Herbert and Robertson, 1991) but pine, wattle and eucalypt plantations all had the tendency to acidify the soil and to change the nutrient cycles from rotation to rotation.

The ability to retranslocate nutrients is highly developed in trees. Trees retain large amounts of nutrients within them, especially in the foliage and stem and they have a remarkable ability to immobilize and re-use the nutrients to support growth in the short and long term (Nambiar, 1984). The concentration of nutrients in the falling needles varies according to cyclic movement in the forest ecosystem. These cycles are observed between juvenile and mature foliage, seasonally within the life of a plantation and rotationally. These variations in nutrient levels need to be taken into account when the nutritional status of a forest is studied and nutrient samples are taken. How this affects sampling is discussed in **Section 2.5.2**.

2.5 The nature of stress

Stress is a change in physiological processes of a plant brought about by one or a combination of environmental and biological factors (Hale and Orcutt, 1987). The potential result of this stress is injury to the plant and ultimately a reduction in growth and production. Optimum growing conditions occur when zero stress is encountered in the environment. Subsequent variation from the point of optimum environmental conditions leads to stress. Zero stress is not readily encountered and can be seen as a theoretical concept.

Strain is defined as the proportional change in a substance as a consequence of stress. Strain can be characterised as physiological change that occurs in response to environmental stress that does not necessarily result in significant reduction of growth or reproduction (Nilsen and Orcutt, 1996). Seeds are a common feature whereby stress (as drought) is abridged.

Stress can also induce tolerance as a means of acclimation. A plant might be susceptible to stress during one part in its life cycle. This form of resistance may change the metabolism and /or the morphology of a plant and ensures its survival in the new environment as a hardened element (Hale and Orcutt, 1987; Nilsen and Orcutt, 1996). For the agriculturist or forester the strain and tolerance (thus morphological anomalies) that accompany stress, mostly result in loss of growth and production or in a product of inferior quality.

Nutrient stress in a tree is the result of absolute nutrient deficiencies or nutrient imbalances in the soil or in the plant. Nutrient disorders can be diagnosed by various chemical, bio-chemical or visual analyses. The result of an analysis is however often restricted to the use of critical nutrient concentrations in the plant or soil (Miller *et al.*, 1981).

2.5.1 Conditions causing nutrient stress

Abiotic and biotic agents of disease affect tree health. In this sense disease is defined as any deviation in the normal functioning of a plant caused by some type of persistent agent that may include aspects of the physical environment (Manion, 1981). The most important single factor that causes nutrient stress in plants is the soil. Nutrient imbalances can also be brought about by air pollution, high temperatures, freezing temperatures, pesticides, drought, fungi, bacteria, viruses, mites, nematodes and parasitism/competition of other higher plants (Miller and Gardiner, 1997).

2.5.1.1 Soils

The complex interaction between various physical factors of the soil, such as moisture, oxygen, mineral content, structure and profile with tree health make the identification of single stress-causing factors very difficult (Manion, 1981). Soil chemical factors such as pH, salinity and nutrient availability determine the distribution of natural vegetation and thus serious nutrient deficiencies are uncommon in natural forests. Exotic trees, alien to sites they have been planted to, may however experience nutrient deficiencies (Manion, 1981; Marschner, 1997). These deficiencies are inherent to the site or could be manifested by cultural activities and should be corrected by appropriate fertility management.

Water is a prerequisite to life and states of limitation or excess in the soil are detrimental to the growth and functioning of tree roots. Waterlogged and flooded soils change soil chemical factors and cause unwanted plant responses of waterlogging injury like epinasty, wilting and leaf senescence. In waterlogged soils the air is displaced from the pore spaces and a state of oxygen deficiency exists. This is termed anaerobic conditions and the soils are said to be hydromorphic. In soil, the change from aerobic to anaerobic condition may occur within millimeters and even in an aerobic soil the soil aggregates' interior may be anaerobic (Marschner, 1997; Miller and Gardiner, 1998).

When oxygen is depleted by the respiration of microorganisms, an alternative source of electron acceptor is found from N, Mn and Fe. The soil redox potential and the presence of specific nutrients determine the sources of electron acceptors. Nitrate is reduced to NO^-, N_2O, NO and N_2 during the process of denitrification and this could negatively

influence the fertility of a site. With continued hydromorphic conditions, manganese oxides (Mn^{4+}) are the next electron acceptors. In acid soils that are high in Mn-oxides and organic matter, but low in N, very high levels of Mn^{2+} can build up in a short time and could result in unfavourable conditions and limit the uptake of other nutrients. Under longer condition of watterlogging the reduction of Fe occurs. This is associated with a drop in soil pH and an increase in the solubility of P. The reduction of S may decrease the solubility of Fe, Zn and Cu by the formation of sparingly soluble sulfides (Marschner, 1997). Deficiencies of these nutrients, especially of Zn in rice paddies, are well-documented as are other mineral deficiencies that occur on a limited scale in poorly drained sections of plantations (Manion, 1981; Snowdon, 1983).

Tree plantings in hydromorphic patches have met with high mortality and poor growth. In the North Eastern Cape these soils are identified and left fallow or planted with more resistant species e.g. *P. elliottii* is planted rather than the ill-suited *P. patula* (Zwolinski, *pers. comm* 1998.).

Nutrients come into contact with tree roots for absorption through mass flow, diffusion or by roots growing towards mineral nutrients. In all cases the presence of water is required and under conditions of water stress the uptake of certain nutrients is retarded. In afforested areas the seasonal occurrence of B deficiencies under conditions of water stress is well known and documented (Snowdon, 1982; Snowdon, 1983; Veijalanen, 1983; Will, 1985; Lambert and Ryan, 1990; Bell, 1997; Shorrocks, 1997). Snowdon (1983) found that soils seasonally subjected to waterlogging and drought showed the greatest degree of B deficiency. Similar problems in some tree growing areas in South Africa is being investigated (Bard, 1997).

Soil acidity limits the growth of plants in many parts of the world. The inhibition of plant growth is caused by a variety of specific chemical factors and interactions between these factors. Marschner (1997) found that the major constraints in acid mineral soils to plant growth is the following:

i) Increase in H^+ concentration (H^+ toxicity)
ii) Increase in Al concentration (Al toxicity)
iii) Increase in Mn concentration (Mn toxicity)

iv) Decrease in the macronutrient cation concentration (Mg, Ca, K deficiency)

v) Decrease in P and Mo solubility (P and Mo deficiency)

vi) Inhibition in root growth and water uptake (nutrient deficiency, drought stress, increased nutrient leaching)

Forest soils are typically acidic (red, apedal, well weathered soils of the Natal Midlands, Mpumalanga and the North Eastern Cape) with deficiencies of Ca and Mg. In the topsoil of organic rich soils, H^+ toxicity is found and Al toxicity in the subsoil is expected. In soils that are high in exchangeable Mn^{2+}, manganese toxicity may become a major factor in soil acidity stress (Marschner, 1997). As the pH of a soil falls (increased H^+) the uptake of cations is inhibited by the impairment of net extrusion of H^+ by the plasma membrane and a decrease in the loading of polyvalent cations (Mg^{2+}, Ca^{2+}, Zn^{2+}, Mn^{2+}) in the apoplasm of the root cortical cells occur. Aluminium is a stronger competitor for binding sites in the apoplasm and a result of this toxicity is that the uptake of Ca^{2+} is blocked. This could be the same for Mn toxicity that inhibits Ca and in particular Mg uptake and can induce Fe deficiencies (Reuter and Robinson, 1997). An excess of Mn in Mpumalanga has also been found to negatively influence the uptake of Fe in soil through oxidation to the Fe^{3+} state. Marschner (1997) reports that the uptake of K is usually unaffected by the Mn and Al content in the soil, which is in conflict with observations made by Schutz (1989) and Viljoen (1991) who investigated a possible antagonism between K and Mn in Mpumalanga.

With increasing soil acidity, root penetration into the subsoil is chemically inhibited (lower Ca/Al and higher Al^{n+}/Al_{tot} ratios) with a resultant shallow root system and less utilization of mineral nutrients and water in the subsoil. The effect of Al toxicity is expressed both as an induced deficiency of mineral nutrients (such as Mg) and inhibitor of root growth. Underdeveloped root systems will not have the capacity for the uptake of P, and unless mycorrhizas are present, P will become deficient. The presence of physical soil barriers (compacted layers, ploughpans, etc.) that lower the effective rooting depth of the soil and thus the effective root foraging volume, has similar results with detrimental effect on tree growth.

Poor physical soil problems have been suspected to be the cause of seedling mortality and stunted growth on previously cropped lands in the North Eastern Cape (Smith and Van

Huyssteen, 1992; Louw *et al.,* 1994; Ellis and Wiese, 1998). Poor growth has been attributed to nutrient shortages that are brought about by restricted root growth in soils that have lost their soil physical properties. In various studies done in the North Eastern Cape the aggregates in the topsoil of good growing areas were compared to poor growing areas and were found to be much more stable. Poor topsoil stability will affect root growth in that soil aeration is negatively affected and water runoff is increased. This creates water loss; drought stress is increased and possible nutrient imbalances (amongst unwanted growth factors) are produced in a web of complicated interactions.

A deficiency in nitrogen (induced by incomplete assimilation of the nutrient in the plant) has been described by Hale and Orcutt (1984) as the first signs of drought stress. The seasonal variation in foliage colour observed in some forestry areas of South Africa from healthy green in the rainy and growing season, to the yellow foliage colour in the dry season at the end of winter are symptomatic of a nitrogen deficiency. Foliar samples that were taken by Noble (1990) to confirm a N deficiency however showed no difference between green healthy trees (1.21 %) and yellow stunted trees (1.23 %) in the North Eastern Cape.

Unchecked fertility of the soil (as one of numerous possible reasons) through excessive fertilisation (P and K) of previously cropped lands has been suggested by Zwolinski (*pers. comm.,* 1998) as being responsible for the growth imbalance between above and below ground parts. High soil fertility, along with adequate moisture in the rain season, does not encourage strong root growth. Growing energy is then channeled to top growth and to the eventual detriment of the tree in the dry season when soil moisture is retracted to beyond the reach of roots. The change in growth pattern results in tip-dieback, stunted growth and yellowing of foliage as symptom of nutrient stress. Investigations of stem deformations in pine trees grown on previously agricultural land in Australia (Carlyle *et al.,* 1989) concluded that the syndrome (called the 'Toorour-syndrome') is associated with very fertile ex-pastures with a high rate of NO_3-N. The investigators further concluded the problem to be independent of soil type or lithology and that the deficiency of a single nutrient element is unlikely. In studies done by Birk (1990, 1991), she found that poor tree growth and deformities were more severe on highly improved soils with high nitrification potential. Plants growing on soils with low pH and high nitrification rates

(thus high NO_3-N uptake) have been identified by Gupta (1997) as being potentially deficient in Mo.

Soil is the largest mineral nutrient pool from where plants absorb nutrients. Excessive amounts of even the most essential elements can be as injurious as nutrient deficiencies (Kozlowski *et al.*, 1986). This is the case with B where the range between toxic and sufficient is very narrow. Until recently is was assumed that forest soils rarely contained excess amounts of nutrients, but air pollution and excessive use of pesticides and fertilisers can modify the soil chemistry and result in the accumulation of toxic amounts of elements in the soil. This may be the source of various nutrient imbalances where industrial fallout occurs.

2.5.1.2 Weeds

Plants are regarded as weeds when they negatively affect the growth of the trees or when they become undesirable. When two plants contend for the same source of light, ion of mineral nutrient, molecule of water or volume of space, they are growing in competition with each other and to the detriment of one or both (Denny and Schumann, 1994). More nutrients are usually absorbed by the strongest competitor, or the plant that is more suited to a particular ecotype and soil environment. This can induce nutrient stress in the other plant that is often the forest seedling. A reduction of soil volume for nutrient absorption increases the risk of nutrient deficiencies developing in the seedling.

Competition between plants can lead to direct antagonism when one plant species adversely affects another by releasing chemicals into the environment. Leachates from leaves are usually the source of alleleopathic chemicals that are toxic to competitor plants. Roots contribute little or no inhibitory chemicals (Schultz, 1997). The effect of possible alleleopathy of weeds in previously cropped lands on the mortality of seedlings have been investigated throughout the world (Smith and Van Huyssteen, 1992; Noble and Schuman, 1993; Schuman and Noble, 1993; Schuman *et al.*, 1994). In South Africa, areas in the Natal Midlands and the North Eastern Cape are thought to be especially prone to this problem. Long term production of continuously grown corn (*Zea mays* L.) and oats (*Tricticum aestivum* L.) and the presence of weeds, that are not as intensely controlled for

forest tree crops as they were for the previous agricultural crops, have negatively influenced tree growth. Growth retardation was also associated with the depletion of soil nutrient reserves by previous crops that cause poor growth on now, infertile soils.

2.5.1.3 Other

Symptoms of mineral nutrient deficiency in plants are often induced by soilborne root diseases or pests that impair root growth and root activity (Marschner, 1997). The interaction between higher plants and parasites and pests are complex and in some cases the role of toxic mineral nutrients and beneficial mineral nutrients are not well established and only understood on an empirical level.

There exists a two-way relationship between diseases and plants:

1. The resistance of a plant is reduced when nutrient stress is present.
2. When a disease is affecting a plant, the ability of the plant to absorb nutrients is diminished by the malfunctioning of plant organs.

Symptoms of fungal diseases, bacterial and viral diseases and pests in forests are often confused with nutrient disorders. This is because of the narrow sense of their existence in plants, the interaction between them and similar conditions under which they occur. In poorly drained, shallow soils the uptake of certain nutrients is restricted and at the same time conditions for infection is favourable.

For some micronutrient disorders factors like light and temperature may affect the appearance and the severity of nutrient disorders. Symptoms of Zn deficiencies are more severe at high light intensities than in partial shade and are more acute in summer than in winter. In field crops Fe, Mn and Zn deficiencies are increased by a combination of low temperatures and high soil moisture. In *P. radiata* Mg deficiencies occasionally occurred in the spring of drought years (Mead, 1984).

2.5.2 The measurement of nutrient stress

2.5.2.1 Diagnosis by symptoms

Impaired metabolism or the disruption of specific processes within plants causes visible symptoms of nutrient deficiency and toxicity. Some symptoms are well defined to permit identification of the disorder, but a number of distinct symptoms may be produced by various disorders that could complicate visual diagnosis of a nutrient imbalance (Reuter and Robinson, 1997).

There are three distinct advantages for the use of visual symptoms to diagnose nutrient disorders:

(i) Diagnosis can be immediate

(ii) Diagnosis can be done in the field

(iii) It is not dependent on laboratory support services

The problem with visual diagnosis is that once symptoms of nutrient stress become visible, yield production is already reduced, permanent malformation could have resulted and no corrective measures may be possible during the remainder of the particular growing season. Mead (1984) found that precise diagnosis is made difficult where incipient deficiencies of many nutrients only cause mild chlorosis or where symptoms appear from a transient situation with negligible growth reduction. Where multiple deficiencies (complex symptoms) occur, another may overshadow one deficiency and corrective measure may not have the desired effect. Symptoms of the most limiting nutrient may be exhibited and with the application of the nutrient, new symptoms can appear that are characteristic of the second limiting nutrient. Due to the natural genetic difference between all trees, the deficiency symptoms can vary according to the intensity of the deficiency and to the degree the plant experiences it. This difference is apparent between varieties, provenences and species.

Diagnosis is complicated by similar visual symptoms being induced by poor physical conditions of the soil, seasonal and climatic effects, damage to roots and stems by fungi or animals, spray damage or pollution effects (Mead, 1984). When the interpretation of visual symptoms is not very obvious, it is recommended by various authors (Mead, 1984;

Dell *et al.*, 1995; Marschner, 1997; Reuter and Robinson, 1997, Schultz, 1997) that other diagnostic techniques or fertiliser trials must be used.

A systematic approach to nutritional diagnosis for seedlings have been developed by Timmer (1991):

(i) Recognition of discoloration or abnormality in growth development during routine inspections. Comparison with other crops of the same age, development stage and cultural regimes.

(ii) Characterization of symptoms is accompanied with detailed description of morphology, appearance, colour and necrosis.

(iii) Elimination of non-nutritional causes based on symptom features and other information (growth records, climate data, cultural treatments) that might indicate that disorders are not nutritionally related but suggest other causative factors such as insect, disease, temperature, moisture, chemical or mechanical.

(iv) Consultation with reference sources such as photographs to arrive at a preliminary conclusion. Observed symptoms are thus matched against reference symptoms acquired from nutritional studies and fertiliser trials.

(v) Corroboration of initial analysis is done by chemical analysis of plants and soil. Results are compared to reference standards, critical levels, optimum nutrient ratios and analyses with accepted techniques.

(vi) Confirmation of diagnosis is done by successful application of curative treatment with verification by leaving an untreated portion of the crop as control.

Diagnosis based on visible symptoms requires a systematic approach as presented for plants in general by Marschner (1997) in *TABLE 2.4*. In all diagnosis necrosis and chlorosis mostly form the basis of diagnostic criteria. Ferguson and Lewis (1993) use a practical distinction between disorders: one that causes slow and impaired growth without stem malformation and disorders that cause stem and branch malformations. This distinction is used to distinguish between macronutrient disorders (former) and micronutrient disorders (latter) in *P. radiata.*

Criteria for visual distinction in pines can further be separated to disorders in needles, leaders, and branches, and collectively in the crown, density and stem form.

- Needle symptoms: thinner and or shorter, pale colour, spotting, yellowing, bronzing, browning, tufting or rosetting at outer branchlet or stem nodes, twist or crook, tip necrosis and needle fusion.
- Leader symptoms: tip necrosis, twist, crook, droop and/or dieback
- Branch: twist or other distortion, premature shedding of one-year-old needles.
- Crown symptoms: various and reflecting collective symptoms of needles, leader and branches. Yellowing of various parts of the crown is a common disorder. The two most common causes are lime chlorosis (Fe and Mn associated imbalances) and yellowing of middle and lower crown foliage associated with Mg deficiencies. Thin crowns are a characteristic of neglected, but not necessarily unhealthy stands, with low to critical levels of all nutrients, and not especially P.

Table 2.4. *Some principles of visual diagnosis of nutrient disorders (After Marschner, 1997).*

Plant part	**Prevailing symptom**		**Disorder**	
Old and mature leaf blade	Chlorosis	Uniform	N (S)	Deficiency
		Interveinal or blotched	Mg (Mn)	
	Necrosis	Tip and marginal scorch	K	
		Interveinal	Mg (Mn)	
Young leaf blade and apex	Chlorosis	Uniform	Fe (S)	
		Interveinal or blotched	Zn (Mn)	
	Necrosis		Ca, B, Cu	
	Deformations		Mo (Zn, B)	
Old and mature leaf blades	Necrosis	Spots	Mn (B)	Toxicity
		Tip and marginal scorch	B	
	Chlorosis, necrosis		Nonspecific toxicity	

The most common and obvious symptom of nutrient disorders is colour change. Diagnosis on the basis of colour relies on a good relationship between growth, pigmentation and leaf chemistry and if colour differences exist between healthy and stressed trees, it can be used to differentiate between deficiencies and/or the degree of nutrient stress (Mead, 1984). Visual and physical symptoms of various nutrient deficiencies have been associated with colour changes (*TABLE 2.5)* of needles in *P. taeda*

seedlings (Schultz, 1997). Munsell Colour Charts are used to assess colour changes or differences in foliage colour (Wilde and Voight, 1952; Grey *et al.*, 1979; Lindler, 1980; Mead, 1984; Blin and Buckner, 1987) in a system that divides colour in components of hue, value and chroma. Lyle (1969) used needle colour as distinguishing characteristics in a dichotomous key to identify nutrient deficiencies of greenhouse grown *P. taeda* seedlings:

I Resin exudation from needles and/or buds

A Needles 10.0Y5/4 with splotches or 5.0YR5/6

Exudation from buds and needles **(Ca)**

B Needles 7.5GY4/4 or 3/4

Exudation from buds **(B)**

II No resin exudation

A Needle colour 7.5GY

1 Needles 7.5GY4/4 or 4/6 and short, thick and twisted **(Zn)**

2 Needles not short, thick and twisted

a. Some dead needles 5.0RP3/4. Dead needle tips 7.5YR

(1) Some dead needles 5.0RP3/4. Dead needle tips 7.5YR7/4 **(P)**

(2) Some dead needles 10R or 5.0R

(a) Some dead needles 10.0R4/2. Needles spiral about terminals with tufted appearance **(K)**

(b) Live needles 7.5GY7/8 or 6/6 with some dead needles 5.0R6/6. Poor secondary needle development **(Mn)**

b. No dead needles RP or R but ends are 5.0YR5/4, 6/4 or 5/6 with bands at intervals around the dead portions **(Cu)**

B Needle colour 2.5GY

1 Large portions of needles vary in colour

a. Needles 2.5GY7/6. Ends of needles YR or R but never Y **(N)**

b. Needles2.5GY8/6. Ends of needles 5.0Y8/8 before YR and R stages **(Mg)**

2 Needles tend to have a uniform colour from tip to base

a. Needles 2.5GY8/6, 8/8, 8/10. The base of some needles become 10.0Y8/6 as deficiency progresses **(Fe)**

b. Needles 2.5GY6/6 or 5/6. No part of needle becomes Y **(S)**

Table 2.5. *Colour variation and appearance of specific nutrient deficiencies in* P. taeda *seedlings (Schultz, 1997).*

Deficient nutrient	Colour	Appearance	Nutrient Content
N	Yellowish-green	Short stiff	1.2 %
P	Redish-purple	Early abscission	< 0.1 %
K	Purple or brown tips	Top dieback	0.16-0.26 %
Ca/B	Mottled yellow-green	Degeneration of buds, secretion of resin	< 0.8 % (Ca)
Cu	Tan or green-yellow bands		
Mn		Single needles	

The use of colour poses a problem in that determination is subjective and that a range of factors such as moisture stress, fungal or insect attack may influence seedling colour (Mead, 1984). Moisture has been found to affect colour of needles by variation in the moisture content (MC):

- MC from 70 – 200 % : 7.5GY (healthy, dark greenish yellow)
- MC from 40 – 180 % : 2.5GY (light greenish- yellow)
- MC less than 60 % : 5YR (yellowish-red)

The needle colour is not uniform from base to tip and differences between the adaxial and abaxial surfaces can be attributed to shading effect. In a study by Grey *et al.* (1979) colour was measured at the base of needles and at the needle body to decrease the measurement of variability and they found better correlation with needle base colour with Site Index than with needle body colour with Site Index. Due to the subjectivity of Munsell Colour Charts, measures of narrow-band width reflectance spectral intensities are becoming the norm in quantifying colour. Good correlation have been found between leaf N concentrations and reflectance intensity (Mead, 1984).

The logical ordering of symptoms are functionally grouped in hierarchical text keys, as was done by Lyle (1969) that used colour as distinguishing characteristic. This method assists in visual diagnoses of disorders and can be generic or be adapted for various species under different growing conditions. A hierarchical text key for the diagnosis of nutrient deficiencies, toxicities, insect and fungal disorders in *P. radiata* was developed by Turner *et al.* (1979) (*TABLE 2.6)* and a key for deficiency symptoms in *Eucalyptus* spp. by Dell (1996) (*TABLE 2.7)*.

Table 2.6. *An example of a hierarchical text key for diagnosis of nutrient deficiencies, toxicities, insect and fungal disorders in* Pinus radiata (*Turner* et al., *1979).*

			Primary symptom	**Probable cause**
A1			Brown or orange needles on a significant percentage of tree and/or dead topping (if not go to A2)	
	B1		Patches of stands with brown needles often from base up	
		C1	Trees of all ages affected noticeable on dry ridges. Seasonal, usually after a period of low rainfall	Drought
		C2	Poorly drained areas, all age classes affected	**Phytophthora**
		C3	Usually affecting suppressed trees in stand. Dead topping with needles retained	*Sirex* wasp
		C4	Areas of stand turning orange red to red brown from base up, trees usually under 15 years old. Probably on basalts, poor granites or soils high in nitrogen (fertilised farmlands). Related to low sulphur/boron situations. Brown needles have red bands.	*Dothistroma* infection
	B2		Scorching of needles	
		D1	Coastal situations with one side of tree affected – flagging	Salt toxicity
		D2	Scorch from base up, groups of trees affected especially in hollows	Frost
		D3	One side of the tree affected, distortion may be present	Herbicides
	B2		Dieback of patches of trees less than three years old, usually from top of tree down. Soils derived from basalts or highly weathered granites. At periphery of dieback, expect further zone of deformed trees with dead tips or side branches. Area most affected is in a gully and may be related in some instances to poor drainage. May be secondary infection of *Diplodia* (*Sphaeropsis)* or *Dothistroma* on surviving trees.	S or B deficiency
	B3		Dieback of growing tips repeatedly giving rise to stunted bushes, rounded trees and in highly productive stands, a high proportion of multiple leaders. Soils are basalts, weathered granites or eroded soils. Dead areas in stand. Dead topping may be spread through stand giving a pepper pot appearance.	
		E1	Black or dark brown pith near side of death. Shepherd's crook.	B deficiency
		E2	Resisnosis, with or without **E1**	S or B deficiency
		E3	Wilting effect on side branch giving Shepherd's effect crook with or without **E1** and **E2**	*Diplodia (Sphaeropsis)* infection
A2			Yellowing of needles (if not go to **A3**)	
	F1		Overall pale yellowing	
		G1	Thin crown, fine branches, generally slender trees. Yellowing or pale green appearance of all age classes, stand affected relatively uniformly. Coastal sands and some heavily weathered granites	N deficiency
		G2	Not finely branched, probably more patchy in stand. Usually very productive stands. Basalts and granites.	S deficiency
	F2		Yellowing from base of tree up. Usually on deep sands. Seasonal.	K deficiency
	F3		Yellowing of single needle age classes, starting with oldest. On inspection yellowing may be severe on distal half of needle	
		H1	Older age classes and stem needles brown to yellow. Black shiny elliptical fruiting bodies, opening by central narrow slit.	*Lophodermium* infection
		H2	Older age classes and stem needles brown to yellow. Whitish waxy, rectangular shaped fruiting bodies.	*Cycloneusma* infection
		H3	Bright yellow stem needles or younger seasonal, often appearance of needle ends dipped in paint. Probably seasonal, especially spring.	Mg deficiency
	F4		Youngest needles are yellow to white. Very sudden change. Rare occurrence is usually found on alkaline soils.	Fe deficiency
	F5		Needles are yellow to white – same as above – all soils types.	Triazine/Triazole herbicide spraying
A3			Yellowing or brown needles not most obvious symptom. Trees generally remain green or grey green.	
	I1		Thin crowned trees causing stem and branches to be obvious especially in younger trees. Fuses needles and rosetting on some trees. Poor and uneven growth. Generally on sedimentary soils, poor granites or coastal sands. In less severe stages may be yellowing on needle tips. Range of symptoms occurs in one stand. Most severe stage in older trees will be death of older needles and top of tree.	P deficiency
	I2		Trees generally older than 15 years. Repeated dieback of trees leading to flattened appearance. High coning may appear. Soils usually similar to phosphorus deficiency sites.	Ca deficiency
	I3		Rosetting – lateral branches short and at an acute angle with short needles. Only late formed needles of current year retained.	Zn deficiency
	I4		Dark blue-green foliage, distorted branches and bushiness.	Cu deficiency
	I5		Paleness of foliage, especially towards top of tree.	Mn deficiency

Table 2.7. *Key to deficiency symptoms in* Eucalyptus *spp. (Dell, 1996).*

				Primary symptom	Deficient nutrient
A1				Symptoms appear first or are more severe on old leaves	
	B1			Leaf colouration is uniform over whole leaf	
		C1		Leaves pale green to yellow, small reddish spots may develop secondary	N
		C2		Leaves green with reddish blotches or leaves uniformly purple to red	P
	B2			Leaves colouration forms a pattern	
		C1		Leaves with marked interveinal chlorosis	Mg
		C2		Leaves with scorched margins or interveinal necrosis, sometimes preceded by marginal chlorosis	K
A2				Symptoms appear first or are more severe on expanding leaves	
	B1			Dieback is present at shoot apex	
		C1		Nodes enlarge, proliferation and death of lateral shoots	
			D1	Leaves with corky abaxial veins or apical chlorosis or malformed with incomplete margins	B
			D2	Leaves with irregular or undulate margins, some interveinal chlorosis	Cu
		C2		Nodes normal, leaves buckled due to impaired marginal growth	Ca
	B2			No dieback at shoot apex	
		C1		Leaves normal size	
			D1	Leaves pale green to yellow	S
			D2	Leaves yellow with green veins	Fe
			D3	Leaves with marginal or mottled chlorosis, small necrotic bleached or brown spots may then appear	Mn
		C2		Leaves small and crowded	Zn

2.5.2.2 Rapid field tests

Quasi-chemical analyses can be done in the field to determine the presence and amount of some macronutrients. Test kits are available, but results are not as accurate as chemical analyses that supply actual values of nutrient content in a plant organ. These kits are used in preliminary soil and foliage analyses where colour coding and changes in colour of solutions are a measure of nutrient availability. Field tests have been used for quick estimates of N, P and K. These tests were done on chopped plant material to measure the nutrient amounts in the plant sap. Although useful, these tests are not precise enough for diagnostic purposes (Miller and Gardiner, 1998)

Field tests have been successfully used where poor lignification of wood leads to the drooping effect and malformation of shoots. This condition is caused by the absence of B, Cu and Mn and with simple in-field tests, the evaluation of lignin-like substances can indicate possible B, Cu and or Mn deficiencies. Dell *et al.* (1996) describe the procedure where the application of a drop of phloroglucinol in 70 % ethanol and a drop of concentrated HCl to a freshly cut eucalypt branch can point to such a deficiency. Lignified wood stains a deep cherry red and in the absence of colouring, nutrient deficiencies must be strongly argued as a possible reason for the growth disorder.

2.5.2.3 Biological assays

Biological assays can include pot trials, field trials, short-term laboratory studies and the use of indicator plants (Mead, 1984). Pot trials and field trials are often used in forestry (Snowdon, 1973; Schutz, 1976; Pritchett, 1979; Crous *et al.* 1995) to determine minor element deficiencies and to evaluate responses to added nutrients with results that are easy to interpret.

Pot trials allow for the acquisition of data over a relatively short time period with control over field conditions. Pot trials that are done on a problem soil and with the application of a variety of nutrient treatments is seen by Mead (1984) as a useful technique to identify nutrient disorders. He recommends that pot trials should be used in the early research phases of site problems. Trials in pots take on the form of subtractive tests (one nutrient is withheld from a complete nutrient treatment) or to test responses to various fertiliser applications. Subtractive trials do not give any information about interactions but they can give a measure of the relative importance of multiple deficiencies (Mead, 1984; Pratley, 1994). Pot trials are also used to determine the potential nutrient supplying power of a soil with trees been grown until nutrient exhaustion occurs.

The problem with pot trials are that they are not suited for extension purposes (Mead, 1984) and results cannot be extrapolated to field conditions. The changing rate of nutrient cycling in a tree with age, make the results of fertiliser pot trials only applicable at planting (Schutz, 1979; Pratley, 1994). A major limitation of pot trials is found with the

collection of the soil and when only a limited part of the soil profile is removed. When the soil is potted, the physical environment and the soil chemistry is changed. Gentle and Humphreys (1968) found large differences in N, Ca, Mg, K, Na and Al foliar levels between pot and field trials on the same soil. Pratley (1994) found pot trials to be of little use in investigations of N and S.

Mead (1984) sees field trials as the ultimate test for the diagnosing of nutrient deficiencies, evaluation of responses to added nutrients and for the calibration of other tests. There is however uncertainty whether the added nutrients are sufficient, that all the nutrients have been absorbed by the trees (none lost to leaching) and that all the relevant nutrients have been applied.

2.5.2.4 Soil analysis

Chemical soil analyses indicate the potential availability of nutrients that roots may take up under conditions favourable for root growth and root activity (Marschner, 1997). A common error is to assume that a soil test alone can function as an absolute predictor of plant growth and thus more is expected of the analysis than the method allows. No quick laboratory test can duplicate the actual uptake of ions by roots and laboratory tests are arbitrary and empirical (Miller and Gardiner, 1998). Soil analyses are nevertheless one of the few methods available for assessing fertiliser requirements for the afforestation of new land.

Problems associated with soil analyses are:

- Selecting representative samples
- Lack of basic information on nutrient requirements of principal tree species
- Lack of information of root zones in which forest trees feed
- Lack of correlation data for interpreting and calibrating tree response to fertiliser application
- Uncertainty which fraction to extract
- Complicating role of mycorrhizae
- Information about microbial activity and plant factors is not supplied
- Rate of supply to plant is difficult to estimate

- Limited use for S, N or minor elements (Schutz, 1979; Pratley, 1994; Marchner, 1997).

Soil analyses make it possible to identify deficiencies and imbalances in the soil. Measurement of the soil pH gives a clear indication of what nutrient imbalances to expect under acidic or basic conditions. A soil analysis also assists in classification by the grouping of similar soils with similar predicted responses into management categories for planning purposes. Miller and Gardiner (1998) describe soil tests, as they are now used, to be generally good for the determination of P, K, soluble salts, pH and lime requirements. Tests that are done for NO_3- N are useful and correlation with crop production is improving, but soil N tests are still not widely established. Tests for other nutrients are improving and varying degrees of success are obtained for Mg, S, B, Zn and Fe. Values for accepted amounts of certain nutrients and indices are presented in *TABLE 2.8*. Values in the topsoil for K, Ca and Mg in *TABLE 2.8* was reported by Drechel and Zech (1993) as deficient for *P. taeda.*

Table 2.8. *Ranges, ratios and indices of soil characteristics where nutrient imbalances may occur.*

Nutrient/Index	Extraction method	Deficient/ Problematic	Acceptable range/ratio
P	Bray -2	6-12 ppm	> 12 ppm
P	Mehlich's P	5-6 ppm	
P adsorption		500- 1000 mgP/kg	100-500 mgP/kg
Base saturation			50-95
Acid saturation			5-15
Al saturation		> 15	< 15
K	1 % citric acid	10 ppm	
Ca	1 % citric acid	30 ppm	
Mg	1 % citric acid	10 ppm	
Ca/Mg			1.5-4.5
Mg/K			3-4
(Ca+Mg)/K			10-20
Cu			5
Zn			3
B			3
Mn			300

A large part of the forest industry in South Africa is situated on highly weathered red, dystrophic soils. The greatest nutrition problem is that of acidity where the effect of Al and Fe oxides influences plant available P. The indirect measure of Al extraction thus provides an index of P retention and it has been found to provide a reasonable index in relation to the growth of pines (Schutz, 1979).

2.5.2.5 Foliar analysis

Lagatu and Maume first used the analysis of foliage in the Montpellier District of France in 1924. This approach is based on the concept that the concentration of a nutrient in the plant increases as the availability of the nutrient in the soil increases (Mengel and Kirby, 1978). Initially research concentrated on grapevines but this system of determining the nutritional status of a plant increased in popularity after the Second World War. In forestry the use of foliar analyses has become a valuable tool, but only within certain parameters and with clearly defined objectives.

The use of foliar analyses can be a simple and accurate way to measure the amount of certain nutrients in a tree but has in the past only been used as a supplement to soil analyses. This caution has been justified by the limited knowledge about the processes of nutrient translocation, luxury uptake, nutrient interactions and the effect of the environment on these processes. The interpretation of foliar analyses has thus been described as more of an art than a science (Hale and Orcutt, 1987). Plant analysis has generally been regarded an empirical exercise because of a rudimentary understanding of the physiology of elements in plants (Ulrich, 1952). Many studies have indicated a correlation between nutrient concentration in plant organs and growth, but a positive correlation may be inferred between the internal nutrient level and the nutrient supply (Schutz, 1979). The correct use and interpretation of foliar analyses has become a fundamental part of nutritional studies.

Nutrient cycling influences the movement of nutrients throughout the tree and with the following factors, cause changes in the nutrient levels of the foliage (Schutz, 1979; Mead, 1984; Marschner, 1997; Reuter and Robinson, 1997):

- Climate
- Daily, seasonal and annual variation
- Tree age
- Between tree variation
- Position in the crown
- Aspect
- Age of foliage
- Nutrient balance

- Site and treatment differences

Partitioning and remobilization of nutrients take place when excess nutrients are absorbed. Nutrients are translocated to storage organs after excess absorption or during periods of nutrient stress when mobile nutrients are transported to areas of deficiency and to buffer low nutrient concentrations. The fluxes of nutrients in *TABLE 2.9* are important to remember when sampling or interpreting analyses.

Table 2.9. *Fluxes of nutrients to be considered with foliar analysis and interpretation (Schutz, 1979; Schönau, 1981(a); Mead, 1984; Schutz and De Villiers, 1987; Schultz, 1997)*.

Nutrient	Species	Influencing factor	Description	Effect
N, P, K, Ca, Mg	Pine	Climate	Wet years	High uptake
N			Dry years	Reduced levels
B	Pine	Climate and season	Cold, wet winters or dry winters	Reduced levels
Zn	Pine	Season	Variation during season	Low
Cu	Pine	Season	Variation during season	High
N, P, K	Pine	Season	Late in growing season	Lower levels
Ca, Al	Pine	Season	Late in growing season	Accumulation
N	Pine	Daily	Night	Higher levels
K	Pine	Yearly	Variation in content	High
Ca, Zn	Pine	Tree age	Increased age	Constant levels
Mg, Mn	Pine	Tree age	Increased	Increases levels
P, K	Pine	Tree age	Until canopy closure	Increase
P	Pine	Tree age	After canopy closure	Constant or decrease
K	Pine	Tree age	After canopy closure	Decreased
N, P, S, Cu	Eucalypt	Tree age	Increased age	Decreased levels
K, Ca, Mg, Zn, Mn	Eucalypt	Tree age	Increased age	Constant levels
Fe	Eucalypt	Tree age	Increased age	Increased levels
N, P, K	Pine	Between tree	Coefficient of variation	5-8 %
Mg, Ca	Pine	Between tree	Coefficient of variation	25 %
Cu	Pine	Between tree	Coefficient of variation	5 %
B	Pine	Clones	Clones in adjacent rows	High variability
P, K	Pine	Crown position	Upper whorls	High levels
Mg, Ca	Pine	Crown position	Mid-crown, lower crown	High levels
N, K	Pine	Crown position	Shaded needles	High levels
N, K	Pine	Crown position	Exposed to strong light	Low levels
B, Zn	General	Crown position	High light intensity	Higher CDC
K, Mg, Fe	Pine	Crown position	Lower crown	Best correlation to SI
Ca, P	Pine	Crown position	Upper crown	Best correlation to SI
P	Pine	Foliage age	Increased age	Decreased levels
All	Pine	Foliage age	Increased age	Very variable
N, Ca, S, Zn, Fe	Eucalypt	Rainfall	Higher soil moisture	High variation
P, Cu	Eucalypt	Temperature		High variation

The season and physiological age of the foliage to be sampled have been seen as the most important factors affecting the tissue's mineral composition (Wells, 1969; Schutz, 1979, Lambert, 1984; Marschner, 1997). The nutrient content of plant matter declines with age for most nutrients (with the exception of Ca and sometimes Fe). Studies by Wells (1963; 1969) indicated variation in *P. taeda* needles for different development ages (*TABLE*

2.10) and most workers have now found nutrient levels in one-year old needles for *P. elliottii* and *P. taeda* stable enough for analyses purposes.

Table 2.10. *Variation of nutrient content in* P. taeda *foliage (Wells, 1969)*

Position	%					ppm				
	N	P	K	Ca	Mg	Mn	Fe	Zn	Cu	Al
First flush	1.06	0.112	0.262	0.187	0.139	248	64	38	2.3	186
Second flush	1.25	0.121	0.287	0.192	0.155	280	57	37	2.8	181
Third flush	1.19	0.135	0.340	0.143	0.152	294	57	40	4.6	174
Bottom of tree	1.12	0.115	0.455	0.262	0.110	805	72	36	3.1	520

The age for sampling has however still been debated with phenology rather than calendar date being considered e.g. when foliage is fully expanded (Mead, 1984). The optimum time for sampling would be under conditions of maximum stress with relative stability in nutrient content. For the sampling of eucalypts, K is best sampled in the dry season and the other nutrients in the wet season. Schönau (1981) found that the variation in nutrient concentration in *E. grandis* tended to decrease in winter. This reduction could be ascribed to less rainfall and lower temperatures that effect the variations of N, Ca, S, Zn, Fe, P and Cu.

Expanding leaves are a sink to nutrients and Marschner (1997) favours the sampling of young leaves for mineral nutrients (Fe, Cu, Mo, Zn) that are not retranslocated or retranslocated only to a limited extend. Mature leaves should be analysed for the measurement of readily retranslocatable nutrients (N, P, K, Mg). Nutrient levels tend to be more stable in autumn and winter and this is often when sampling is recommended. Leaching of mobile nutrients (like K) from foliage due to rain prohibits the sampling during or after rains. This could only increase the variability found in foliar analyses.

In a study by Payn and Clough (1987) they found that elemental concentrations in pine trees of the Southern Cape vary seasonally. The most stable period is during winter and that is when they recommend foliage to be sampled. The order of annual variability is Al>Ca>Mn>K>N>P. The winter season is a period of accumulation for N, P and K, but during the growing season, when trees are under physiological stress, the nutrient levels drop. The drop in nutrient levels is the result of translocation of elements from the mature needles to the growing tips, or a possible dilution effect.

2.5.3 Confirmation of a deficiency

The development of soil and tissue analyses has allowed for the quantification of nutrients by means of a single value. Were it as simple to compare an analysed value to a given value of adequacy/deficiency, the task of the nutritionist will be overly simplified. The variation in nutrient levels within a tree and between trees of the same genera (as only two sources of variation), has in itself, resulted in such a diversity of nutrient levels that it is with trepidation that most nutrient imbalances are diagnosed without observing clear cut disorders. A holistic approach is needed where the results of chemical analyses are used in conjunction with observations (visual diagnosis) made in the field.

2.5.3.1 Critical values

The relationship between the concentration of nutrients in plant tissue and the growth of a plant has been used in the diagnosis of nutrient imbalances. The aim being the determination of a critical nutrient concentration above which there is no significant increase in growth (Dell *et al.,* 1995). Growth is thus theoretically limited by a particular nutrient (The Law of Minimum), but because of the intricate relationship between all nutrients, the critical level of a particular nutrient should be determined under conditions of adequate supply of all other nutrients.

The critical levels for a specific part of the tree and the stage of development should be specified. Variation in nutrient content of pine needles with season, age, soil, and position in the crown has been extensively researched by various authors (Wells and Metz, 1963; Miller, 1966; Schutz, 1979; Miller, Miller and Cooper, 1981; Rathfon *et al.*, 1993, Reuter and Robinson, 1997; Marschner, 1997) and conflicting results and conclusions abound. Rathfon *et al.* (1993) distinguish between diagnoses for fertiliser recommendations and diagnoses where the sampling criteria require maximum sensitivity to site or experimental treatment differences. In the nutritional analysis of a large forest area (and with broad management options in mind), it is sensible to analyse the nutrient content of the foliage at a stable stage in the growth cycle of a tree. This stage concurs to

a period of minimum growth (when nutrient demand is low) and usually when the environment becomes harsher and the tree is under maximum stress, e.g. winter. For use in trials, Rathfon *et al.* (1993), found that sampling under conditions of peak nutrient demand was a good indicator of treatment differences.

The acquirement of norms used as critical levels are difficult to establish and it may take years of sampling and analyses before a critical range of a particular nutrient for a particular tree species can be narrowed down to acceptable values with a high confidence rating. This problem, as recognized by Glen (1973), can further be expanded to the physical and chemical properties of soil. Norms should then be established for each soil type on which forest trees are cultivated. Standardisation between analytical laboratories is of paramount importance.

The recent advances that have been made in modern measuring instruments have increased the accuracy of analytical techniques (Reuter and Robinson, 1997). A higher degree of sensitivity to narrower nutrient concentration limits in the plant can thus be measured. It can then be debated that this sensitivity increases the spectrum of nutrient values from whence adequacy levels are predicted, and that the diagnosis of nutrient disorders is only more complicated. It has been shown that plants have the ability to regulate the nutrient concentrations in their tissues, but the amounts of nutrients are always limited to the external supply.

The use of a range of values for defining nutrient content where deficient growth occurs, seems to be more appropriate and realistic than a single value. The range of foliar mineral nutrient concentration given for the various species (*APPENDIX 3)* is devided into the system used by Van den Burg (1985):

- Occurrence of visual symptoms of deficiency:

(i) Observed values of concentrations found in plants in combination with visual deficiency symptoms

(ii) Threshold values where considerable growth reduction occurs and symptoms of a deficiency occurs

- Concentrations that are usually higher than the threshold value of visual deficiency but associated with poor or insufficient growth. This is called the low range (sin. deficiency or insufficiency ranges).

- Intermediate range is where acceptable growth occurs. There are no visual symptoms of deficiency and a positive reaction to fertilisation is likely (sin. adequate, sufficient, and normal).
- Optimum range is the plateau part of the growth response curve where increases foliar concentration does not increase growth or yield.
- High range concentrations are not fully understood. The nutrient concentrations are exceptionally high in comparison to the lower and optimum range, but no growth or yield depressions are visible.
- The toxicity range is where the content of foliar nutrients are so high that the rate of growth is depressed. It is divided into :

(i) Threshold values – where the growth response curve shifts from the horizontal to a downward curve.

(ii) Observed values – values that are not threshold values.

Since the concentration of a nutrient in plant tissue is the resultant of two dynamic processes, nutrient uptake and dry matter accumulation, the concept of critical nutrient content should be viewed in a balanced way.

2.5.3.2 Nutrient ratios

Nutrient ratios have been used as an aid in the interpretation of foliar analysis. This is to overcome the weaknesses of the critical level approach and to include the concepts of intensity and nutrient balance (Mead, 1984). These concepts recognize that the balance of nutrients is more important than the total amounts of nutrients in the plant. Growth is dependent on the proper amounts and proportions of nutrients and maximum yield can only be attained when an optimum level and an optimum balance is present in the plant (Timmer, 1991; Miller and Gardiner, 1998). Nutrient ratios are not only an indication of balance, but it is less influenced by annual variations. The absorption and accumulation of one nutrient affect the status of other nutrients and thus a quantitative method for evaluation of these interrelationships is required.

The most common method of expressing balance is by describing the relationship of each nutrient to N. Studies found that the balance between seedlings of various species is

remarkable similar when grown in a solution culture but that ecological difference might come into play. Van den Burg (1988) has developed three criteria for the classification of nutrient ratios:

(i) Relationship of nutrients expressed to N

(ii) The relationship of each cation nutrient

(iii) The relationship of N:Cu

Much emphasis is placed on the relationships of the nutrients to N (*TABLE 2.11*) but differences are still apparent even between ratios for various species given in literature (*TABLE 2.12).* The most important ratios have been found to be N:P and N:S. The N:Ca ratio in conifers has little physiological importance (Van den Burg, 1988) and is not always calculated because the Ca needle content is a relatively good indicator of Ca status.

Table 2.11. *General information about macronutrient (N, P, K Ca, Mg, S) proportions in foliage in many tree species (Van den Burg, 1988).*

Species, groups	**Mineral nutrient status**	**Element proportions**					
		N	P	K	Ca	Mg	S
Many broadleaf species	P,K – optimum	100	10	50			
	P,K – intermediate	100	10-5	50-25			
	P,K – deficient (low)	100	< 5	< 25			1
Many tree species	Visual S deficiency	≥ 20					1
	Intermediate to optimum S	20-10					1
	High S or low N	≤ 10					
Many tree species	Optimum P	100	10				
	Optimum Ca/Mg ratio				7.7	1	
Many tree species	P, K – optimum	100	13 (range 10-20)	54 (range 39-74)			
Many conifer species (seedlings)	P,K,Ca,Mg - optimum	100	2-15	50	50-100	5-10	

The relationship of the cations to the other nutrients plays an important role due the occurrence of antagonisms. The K:Ca and the K:Mg ratios are regarded to be the best indicators of excess cation absorption. In areas where air pollution and excess nitrogen fertilisation has taken place or where Cu deficiencies are suspected, imbalances can be indicated by the N:Cu ratio.

Table 2.12. *Macronutrient proportions (N, P, K, Ca, Mg, S) in the foliage of some tree species (Van den Burg, 1985).*

Species	Age, stand type, etc	Mineral nutrient status	Element proportions (%/%)					
			N	P	K	Ca	Mg	S
Pinus nigra var. maritima	seedlings	Optimal proportions,	100	14	45	6	6	
		Optimal proportions	100	10				
Pinus nigra var. nigra	stands	Optimum N/S ratio	100					7
Pinus strobus	Nursery crop	Healthy			8.57		1	
		Visual Mg deficiency			13.0		1	
Pinus sylvestris	Seedlings on nutrient solutions	Optimum proportions	100	14	45	6	6	9
		Optimum proportions	100	20*	50	5	4	
	seedlings	Intermediate P, K status	100	12	35			
	seedlings	Intermediate P, K status	100	8.7-11.9	32.8-34.4			
		P deficiency	100	7.8-8.1				
		K deficiency	100		4.2-19.3			
	seedlings	Optimum N/P ratio	100	6.7-20				
		Intermediate nutrient status	100	8-15	50-100	5-10	5-10	
	Seedlings (12 months) pot trial	Optimum proportions	100	15	54	22		
	Seedlings (24 months) pot trial	Optimum proportions	100	20	53	27		
	Young plants in pot trial	healthy			1.0-5.35	1		
	Nursery crop	healthy			5.5		1	
		Visual Mg deficiency			12.5		1	
	Nursery crop	Healthy	100		34.4-48.3			
		K deficiency	100		32.3			
		Intermediate K status			0.73	1		
		Low to intermediate K			0.61	1		
		Intermediate Mg	100				5.1-8.6	
		Low Mg	100				2.8	
	Young stands	Intermediate P	100	10				
		Low P	100	7.9				
		Optimum N/P ratio	100	10				
	Stands	Optimum proportions	100	18-25	64-90			
		Optimum proportions	100	9-9.25	43.2			
		Optimum proportions	100	10.4	38.8			
		Optimum proportions	100	10	39			
	Stands	Optimum N/P ratio	100	7.1-7.7				
		Low P	100	<6.2				
		Intermediate K status	100		29			
		Optimum K status	100		29			
	Adult stands	Optimum N/P ratio	100	6.6-11.1				
		Intermediate P status	100	11.1-12.5				
Pinus taeda	Young stands	Low P status	100	<6.7-7.1				
		Low to intermediate N	100	> 6.7-7.1				
	Stands	Optimum N/P ratio	100	9.5-10.5				
Eucalyptus spp.			100	15				
E. grandis	Plantations		100	10-16				

Herbert (1996) and Lindler (1995) use the direct ratio of N to the various nutrients (*TABEL 2.13*) for eucalypts and higher plants respectively. Carlson *et al.* (2000) realized

the disadvantage of using ratios of nutrient balance estimation. In their study they found ratios not unlike those given as adequate for *Eucalyptus nitens*, despite low values for the individual elements (N, P and K). This illustrates the problem that where the levels for two nutrients are low, the ratio may still appear adequate.

Tabel 2.13. *Optimum nutrient ratios for higher plants and* Eucalyptus *spp. (Lindler, 1995 and Herbert, 1996).*

Nutrient ratios	Optimum ratio	
	Higher plants	***Eucalyptus* spp.**
P:N	10	18
K:N	35	3.5
Ca:N	2.5	
Mg:N	4	
Mn:N	0.05	
Fe:N	0.2	
Cu:N	0.03	
Zn:N	0.05	
S:N		14
P:K		0.2
Ca:Mg		> 3.3

2.5.3.3 Diagnostic and Recommendation Integrated System (DRIS)

The bases of DRIS is in the investigation of the relationship between nutrients in a tree or plant and underlies the theory that as plants approach their growth potential, their nutrient status becomes less variable (Needham *et al.*, 1990). DRIS assumes that there is an optimum ratio between any two elements and that deviation from that optimum relationship is indicative of poor growth (Svenson and Kimberley, 1988). It is a system that was developed by Beaufils (1973) mainly for use in the agriculture sector and was first applied in the 1950's in the nutrition of rubber trees in the Far East.

The system has found application in various crops like maize, rubber, sugarcane, wheat, potatoes, soybeans, citrus (Schutz and De Villiers, 1987) and has been used as indicator of environmental stresses such as pollution (Ritters *et al.*, 1991). DRIS has been implemented in forestry as tool in optimising fertiliser prescription (Schutz and De

Villiers, 1987; Ward *et al.*, 1985; Sumner, 1977) and as means for determining critical levels of foliar nutrients (Needham *et al.*, 1990). DRIS has quantitative and qualitative abilities to investigate tree health or yield in a problem area by comparison to calculated norms. It is thus possible to use any characteristics of the plant, soil and / or the environment as the base of comparison, but in forestry the foliar nutrient content has mostly used as calculation variable. Indices that were calculated from leaves were proven to be the only reliable variable to predict deficiencies in a study done by Ward *et al.* (1985) on *Eucalyptus saligna.*

The system is based on the collection of as much data as possible on plant characteristics and this is used for the calculation of optimum nutrient ratios (nutrient indices). There are four steps in the application of DRIS :

1. The creation of a data bank
2. The development of critical norms
3. The calculation of indices
4. The testing of the norms

The creation of a data bank is the arduous part of the process. The data bank for a specific species should contain yield information over a wide range of conditions and the more observation made, the higher the degree of accuracy of the DRIS system (Schultz and De Villiers, 1987). Some studies (Beverly *et al.*, 1984; Beverly *et al.*, 1986, Marschner, 1997) have indicated that regional differences influenced the indicative potential of the system, but it has been advocated that world wide inclusion of data could only strengthen the system (Schultz and De Villiers, 1987) as by the use of maize where thousands of samples were collected internationally (Beaufils, 1971).

In the collection of data partitioning between populations of different yields is required. This is done to ensure lower variance (s^2) and coefficient of variation (cv) (the standard deviation divided by the mean) values within the norms and to increase the accuracy of the system. It is thus normal to divide a population of measurements into subpopulations on the basis of yield (Schutz and De Villiers, 1987). The concept of yield in forestry however needs to be defined (mean height, top height, DHB, basal area, volume, GLD, etc.) to ensure uniformity of yield classification on an international scale.

Data collection should include areas over a range of fertility and soils, site conditions and management practices (Svenson and Kimberley, 1988; Rathfon and Burger, 1991) and then be divided into the subpopulations. Svenson and Kimberley (1988) used a site index of 30 for *Pinus radiata* as means of differentiation , Schutz and De Villiers (1987) used a site index of 18 for *P. patula* and Rathfon and Burger (1991) used age-adjusted ground line diameters between high yielding and low yielding subpopulations. The data were then used to calculate DRIS norms. Variations of expression of the elements collected in the data are determined by as many means as possible. The accepted expression (Schutz and De Villiers, 1987) that is mostly used is the concentration ratio (e.g. N/P). A function for a particular ratio is calculated that is then used to obtain a DRIS index.

Svenson and Kimberley (1988) calculated the ratio function by log transformations of the concentration ratios for the measured and norm ratios and subtracting the inverse of the coefficient of variation (*EQUATION 2.7*). The weight in the cv is felt when there is a large variation in measured values and that the influence of the particular ratio function in the index calculation is thus decreased.

$$f(N/P) = (\log(N/P) / \log(n/p) - 1/cv \quad \text{..... (2.7)}$$

where

f(N/P) = ratio function

log(N/P) = natural log of the measured N/P concentration ratio

log(n/p) = natural log of the norm

cv = coefficient of variation

A decision of inclusion of a particular function ratio in the DRIS index of a nutrient is made on the assumption that high yielding subpopulations are under less nutritional stress than the low yielding subpopulations and that less variation around their mean is expected. Analysing the differences between the variances and the means of the concentration ratios statistically tests this assumption. If no significant differences between the variances and means of the high yielding and low yield subpopulations are apparent, then the particular concentration ratio is not included in the DRIS index. This is an indication of a nutrient imbalance.

Differences between the variances or the means did not qualify as exclusion to the calculation of the index in a study done by Svenson and Kimberley (1988), whilst differences in both the variances and the means where the ideal. In their study, the P/K concentration ratio showed no significant differences between the high and low yielding subpopulations (p values > 0.05) and thus the P-index and the K-index were calculated without that particular ratio.

The function ratios (as calculated in *EQUATION 2.7*) is an adaptation of the functions used by Beaufils (1973) and Schutz and De Villiers (1987) in that the log transformations normalise the distribution of the ratios. This procedure also nullifies the effect of choosing what element is used first in the calculation of the indices (Svenson and Kimberley 1988).

The DRIS index is derived from an equation (*EQUATION 2.8)* where full complements of nutrients are measured and where (in this case) there are significant differences between the high and low yielding populations. If the nutrient in the equation is the nutrient for which the index is being calculated and it is the numerator in the ratio, then the ratio function is positive, if it is the denominator, then its value in the equation is negative. *EQUATION 2.9* illustrates this.

$$\begin{aligned} \text{N–index} = [\ & f(N/P) + f(N/K) + f(N/Ca) + f(N/Mg) + f(N/Na) + \\ & f(N/S) + f(N/Cu) + f(N/Fe) + f(N/Mn) + f(N/Zn) + \\ & f(N/B) + f(N/Mo) + f(N/Al)\ ] / 14 \end{aligned} \quad \text{..... (2.8)}$$

$$\begin{aligned} \text{Cu–index} = [\ & -f(N/Cu) - f(P/Cu) - f(K/Cu) - f(Ca/Cu) - f(Mg/Cu) - \\ & f(Na/Cu) - f(S/Cu) + f(/Cu/Fe) + f(Cu/Mn) + f(Cu/Zn) + \\ & f(Cu/B) + f\,(Cu/Mo) + f(Cu/Al)] / 14 \end{aligned} \quad \text{..... (2.9)}$$

The nutrient with the lowest index (most negative) is the most limiting element. DRIS allows for the ranking of the entire tested nutrients from the least significant influence on growth (highest positive index) to the most limiting nutrient (lowest negative index). The total sum of the indexes is seen as the variation from a point of balance (if the sum values to zero) if the signs are ignored.

The norms that are acquired must be subjected to testing to ensure that meaningful diagnoses and recommendations can be made. Schutz and De Villiers (1987) suggest testing in a fertiliser trial by use of a particular treatment, making a diagnosis, and again testing the recommendation in another treatment that satisfies the recommendations made from the diagnosis.

In agricultural use DRIS has been useful with testing crop response to fertilisation, indicating what nutrients are the limiting growth factors and determining the interaction among them. In an example given by Sumner and Beaufils (1975), the effect of time over the growing season of sugarcane was overcome by the fact that DRIS computes a ratio, and unlike critical nutrient concentration, it does not depend on the dry matter component that changes through the season as the crop matures. This finding (if extrapolation to long term cropping is possible) could simplify the foliar analysis of tree crops to seasonless and stageless collection. Schutz and De Villiers (1987) are optimistic of DRIS capabilities in a forestry setup and states that if certain constraints (like different harvesting ages) can be overcome, DRIS will play an important role in indicating nutrient imbalances and monitoring site fertility.

2.5.3.4 Vector analysis

Vector analysis is a graphical approach to evaluation of the nutrient status of a plant or a tree. It incorporates a unit of dry mass (normally needle mass) as an additional dimension for comparison between a healthy (or control tree) to a treatment tree or an unhealthy tree. Other methods of nutrient determination depend on the chemical concentration of a particular nutrient in the leaf and are thus susceptible to nutrient dilution (Mead, 1984; Timmer, 1991; Reuter and Robinson, 1997; Miller and Gardiner, 1998)

The concentration of nutrients in plant tissue is a resultant of two processes:

1. The amount of nutrient uptake
2. Dry matter production

Timmer (1991) makes use of the relationships between plant growth, nutrient concentration and nutrient content *(FIGURE 2.5)* for the diagnosis of nutrient health. Growth of a plant is expected to be curvilinear but may increase beyond the sufficiency level where luxury consumption or toxicity may occur. He graphically illustrated these hypothetical relationships and explains the changing association between growth and biomass, nutrient concentration and nutrient content for each phase as increasing (+), decreasing (-) or unchanging (0).

If the canopy mass (or dry matter production) increases as a result of a nutrient treatment, then studying the foliar nutrient concentration alone ignores the effect of the nutrient on tree growth. In cases where there are adequate nutrients available for plant development, the growth rate increases and there is a temporary dilution effect on the concentration of nutrients in the plant material. This can be mistakenly diagnosed as a nutrient deficiency.

Vector analysis was developed as a quantitative system for evaluating multinutrient interrelationships in terms of changing nutrient concentration, nutrient uptake and growth of the plant. Vector analysis compares dry mass and nutrient composition of seedlings of contrasting growth (Timmer, 1991) and has been applied in vegetation control studies (Imo and Timmer, 1998; Imo and Timmer, 1999), nutritional studies (Weetman, 1989; Hunter *et al.*, 1990; Timmer, 1991, Imo and Timmer, 1997; Malik and Timmer, 1998) and various fertiliser trials (Weetman and Fournier, 1982; Timmer, 1997).

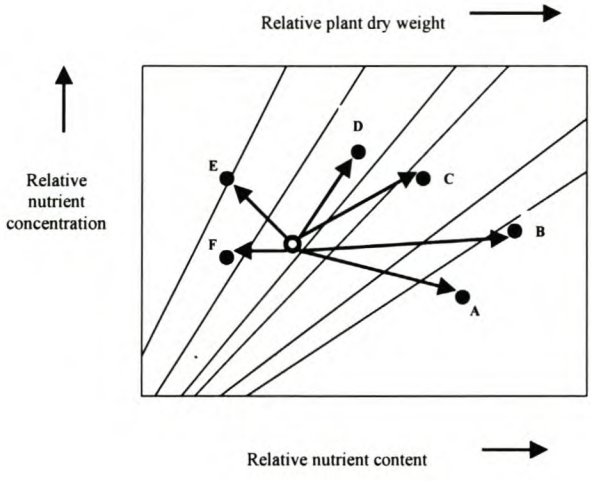
Seedlings that are different in growth (high yielding and low yielding, healthy and unhealthy, desirable and undesirable, with and without visual symptoms) are compared with one another on a dry mass and nutrient composition basis. This is done in a nomogram *(FIGURE 2.5)* where Timmer (1991) developed a relationship between the nutrient concentration (y), nutrient content (x) and dry weight (z) as the following equation:

$$x = f(y.z) \qquad \textbf{(2.10)}$$

Isopleths (diagonal lines in *FIGURE 2.5*) depict the change of y on x where z remains unchanged and is used for distinction between growth measures of the different samples. The arrows in *FIGURE 2.5* are known as vectors and represent the relative difference

between plants of the various growth treatments and the reference (control seedling). Of importance is the magnitude and the direction of the vector that form the basis of vector analysis.

The direction of the shift (from the reference to a particular point) is divided into changes of parameters (either +, 0 or -) and used as a diagnostic guide to nutritional requirements, indications of imbalances or toxicities.



Direction of shift	Change in relative			Interpretation	Possible diagnosis
	Plant weight	Nutrient			
		Concen.	Content		
A	+	-	+	Dilution	Non -limiting
B	+	0	+	Sufficiency	Non -limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury consumption	Non-toxic
E	-	++	+-	Excess	Toxic
F	-	-	-	Excess	Antagonistic

Figure 2.5. *Interpretations of directional differences in nutrient concentration, nutrient content and dry weight between nutritionally different plants. The point in the center is the reference seedling (normalized to 100) and the vectors indicate nutritional shifts as explained in the box above (Timmer, 1991).*

Vector analysis is independent of critical nutrient values, optimum ratios and norms, and because problem seedlings are compared to seedling of associated sample age, development stage and environmental conditions, variation is reduced to the minimum (Timmer, 1991). This system is particularly suited for interpreting complex nutrient interactions and treatment responses.

2.6 Construction of a nutritional map

The areas indicated on the map are not necessarily the only areas in South Africa that experience nutritional problems. Certainly most N, P and K deficiencies are addressed by simple silvicultural techniques and such deficiencies are not frequently observed.

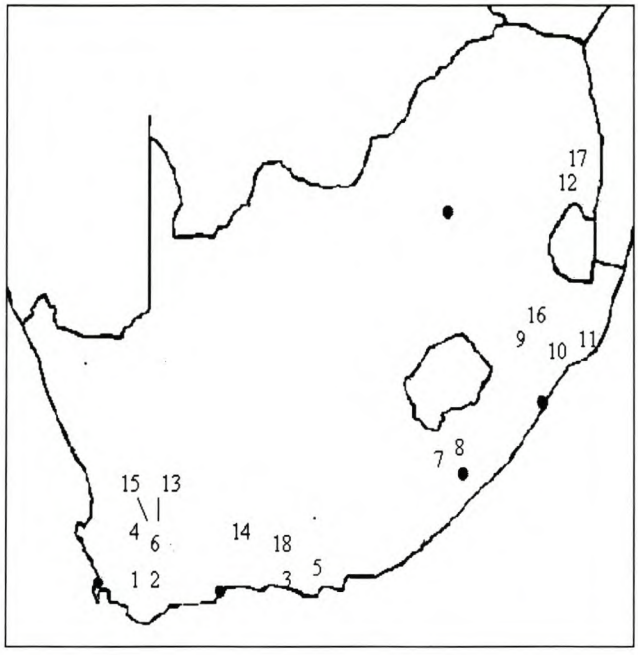


Figure 2.6 *Map indicating areas where nutrient imbalances have been observed or recorded.*

1. Mn deficiency– Grabouw (Ellis, *pers. comm.*)
2. P deficiency – Houwhoek (Ellis, *pers. comm.*)
3. Mn deficiency – South Western Cape (Payn *et al.*, 1988; De Ronde *et al.*, 1988; De Ronde, 1992)
4. Zn deficiency – Kluitjieskraal (Ellis, *pers. comm.*)
5. Zn deficiency – South Western Cape (Ellis, *pers. comm.*)
6. Cu deficiency – Kluitjieskraal (Ellis, *pers. comm.*)
7. Mo deficiency – Ugie, Maclear (investigation, this study)
8. B deficiency – Ugie, Maclear (investigation, this study)

9. B deficiency – Natal Midlands (Bard, 1997; Ellis, *pers. comm.*; Du Toit and Job, 1999)
10. Cu deficiency – Zululand (Anon, 1990)
11. Zn deficiency – Zululand (Anon, 1990)
12. Fe deficiency – Kaapsche Hoop (Ellis, *pers. comm.*)
13. Mg deficiency – Kluitjieskraal (Ellis pers. *comm.*)
14. P deficiency – Robertson Pass (De Ronde *et al.*, 1988; De Ronde, 1992; Ellis, *pers. comm.*)
15. N deficiency – Grabouw (Ellis, 1997)
16. Mg deficiency – Natal Midlands (Du Toit and Job, 1999)
17. Mn toxicity – Kaapsche Hoop, Sabie and Graskop (Schutz, 1989; Viljoen, 1991; Ellis, *pers. comm.*)
18. N toxicity – South Western Cape (De Ronde, 1992)

3. Materials and methods

Investigations of nutrient stress were conducted in field trials in three forestry regions of South Africa (Mpumalanga, Natal Midlands and the North Eastern Cape) (*TABLE 3.1*), and bio-assays in a greenhouse environment at the University of Stellenbosch.

Field trials were conducted in areas where growth aberrations were identified by foresters and researchers. The field trials took on the form of nutrient application to established stands (of various species and ages) and as planted trials. In the pot trials five major timber species (*Pinus patula, P. elliottii, P. taeda, P. greggii* and *Eucalyptus nitens*) were grown on soils collected from the forestry regions and growth responses tested to various nutrient treatments. Two indicator species (soya and cauliflower) were grown in pots on a problem soil from the North Eastern Cape.

The incidence and recording (Smith and Van Huyssteen, 1992; Noble and Schumann, 1993; Schumann and Noble, 1993; Louw *et al.*, 1994; Noble 1994, Schumann *et al.*, 1994; Fyfield *et al.*, 1998) of growth problems in the North Eastern Cape provided the opportunity of an in depth study in that area. Consequently more trials were conducted in the North Eastern Cape. Some trials were done in collaboration with other research institutes and companies.

Soil analysis was done using standard methods (the Non-affiliated Soil Analysis Work Committee, 1990) : pH was measured in 1:2.5 soil to 1 mol/dm^3 KCl solution; resistance of soil paste using an US Bureau of Soils standard electrode cup and resistance bridge; P by using the Bray 2 method; exchangeable cations and CEC by the ammonium acetate method at pH7; Cu, Mn and Zn with di-ammonium EDTA and B and Mo by hot water extraction. Leaf samples were ashed and then analysed using an IGP emission spectrometer.

Table 3.1. *Location of trials and details of current crop.*

Region	Area	Farm/Estate	Lon./ Lat.	Comp.	Species	Plant date
North Eastern Cape	Maclear	Ludano	31°07'S 28°21'E	B01	*P. patula*	1996/11
		Ludano		B04	*P. patula*	1998/12
		Riverside	31°05'S 28°18'E	D08	*P. patula*	1991/02
	Ugie	Feltham	31°06'S 28°13'E	C17B	*P. taeda*	1994/11
		Sonsbeek	31°09'S 28°16'E	G32B	*P. patula*	1998/12
Mpumalanga	Graskop	London	24°50'S 30°55'E	G17	*P. patula*	1994/10
	Kaapsche Hoop	Berlin	25°36'S 30°46'E	P3	*P. elliottii*	1992/10
				M32	*P. patula*	1995/12
Natal Midlands	Mooi River	Harleigh	29°17'S 28°44'E	H22	*P. patula*	1992/03
		Giants Castle		-	*P. patula*	1998/04

3.1 North Eastern Cape trials

3.1.1 Pot trials

3.1.1.1 Liming trial

The objective of this trial was to test the growth response of *Pinus patula, P. elliottii, P. taeda, P. greggii* and *Eucalyptus nitens* seedlings to various micronutrient and lime treatments. The seedlings were grown in pots on a problem soil from the North Eastern Cape.

The soil was collected from the B-horison of a Hutton soil form in the Maclear district, Ludano, compartment B01 (detailed soil analysis in *APPENDIX 2*). The lithology comprises the Molteno Formation that is characterised by grey mudstone, shale, gritty sandstone and occasional coal seams. Texture of the tested horison was a sandy clay loam. Plantings of *P. patula* in the compartment has met with high incidence of seedling mortality and replanting has occurred a number of times. The soil was subjected to previous land use (maize and potatoes).

The collected soil was transported to Stellenbosch, air-dried, sifted and placed into standard size (150 mm top diameter) pots. Equal amounts of gravel was placed in all pots and filled to a specific mass (1.3 kg). The pots contained about 1 dm^3 of soil. To prevent

nutrient contamination from nursery grown seedling stock, four seeds from selected seed sources were sown per pot. Seed sources used were:

(i) *P. patula* : V/N 23443
(ii) *P. elliottii* : V/N 28447
(iii) *P. taeda* : V/N 23288
(iv) *P. greggii* : M 8532

Four weeks after germination, surplus seedlings were pricked out and each pot was left with one seedling. The seedlings were kept in a greenhouse at the University of Stellenbosch where the temperature ranged between 20 to 35 °C during the day and 5 to 15 °C during the night (measured throughout the year). The seedlings were automatically irrigated and care was taken to keep the water content between 40 % and 80 % of field capacity. The soil water holding capacity was determined so that no over-irrigation occurred. Soil water holding capacity is the amount of moisture that a specific weight of soil can retain against the force of gravity. It is determined by percolating water through air dried soil, allowing it to stand for 24 hours and expressing it as a percentage of water retained from the increase of total weight (Malherbe, 1964).

The trial was a 5x2x4 factorial with the main effects being the various species, the addition of lime, and the growth response to a soil added boron nutrient treatment, a foliar molybdenum nutrient treatment and a boron-molybdenum combination treatment (treatment details in *TABLE 3.2*) were tested with eight seedlings per treatment. Boronate is a fertilser manufactured from a combination of colemanite ($Ca_2B_6O_{11}.5H_2O$) and ulexite ($NaCaB_5O_9.8H_2O$) and contains 16.5% B. One pot contained one seedling and amounted to one plot or replicate (single pot plots). The pots were numbered and positioned by random numbers generated by SAS.

Table 3.2. *Treatments applied, their sources, amounts and methods of application.*

Treatment	**Source**	**Amount of source**	**Amount of active ingredient**	**Application**
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.25 g/l	0.10 g/l	Foliar
B	Boronate (16.5% B)	1.5 g/tree	0.25 g/tree	Soil
Mo + B	$Na_2MoO_4.H_2O$ (39% Mo) and Boronate (16.5% B)	See above	See above	Foliar (Mo) and soil (B)

The lime was mixed into the soil to an amount that increased the level of the soil pH to pH 5.5. This was calculated in accordance to the method of Eksteen (1969), using a field factor of 4 (*EQUATION 1).*

$cmol_c$ Ca/ kg of soil required = x = (RH-(Ca + Mg))/ (R+1) ..... *(1)*

where x = the amount of $cmol_c$ H^+/kg soil that must be neutralised
= $cmol_c$ Ca/kg soil ≡ tons of pure lime/ha of topsoil
R = desired ratio as determined by a crop (R = 10 in calculations)
H, Ca, Mg = amounts of nutrient measured in the soil

The seedlings were grown for 547 days during which time height growth, diameter growth and colour changes were measured and monitored. The diameters of the seedlings were measured at ground line diameter (G) and the seedling height (H) from the level of the potted soil to the tip of the growing point. Colour was measured by using the Munsell system of colour charts (Munsell, 1952). Chlorosis, as differences in colour between the treatments was calculated by transforming the colour variables (hue, value and chroma) to a single value, relative to a reference value (7.5GY7/10). At the end of the trial the seedlings were measured (G and H) and then removed from the pots. The soil was washed from the roots, the seedlings dried at 70 °C for 24 hours and the mass of the roots, shoots and needles of individual seedlings were measured. This gave an indication of biomass partitioning to below and above ground biomass portions. A seedling biomass index (BI) was calculated by multiplying the seedling height with the square of the stem diameter. Analysis of all the variables were done by use of the SAS 6.12 statistical package (SAS, 1989). The Student-Newman-Keuls test for variables was used for multiple comparison of treatment means.

3.1.1.2 Ludano nutrient trial

The objective of this trial was to test the growth response of *Pinus patula* seedlings to various nutrient treatments in pots on a problem soil from the North Eastern Cape.

The soil was collected from the same site as the soil used in the Liming trial of **Section 3.1.1.1**. The same methods of soil collection, trial preparation, seed sowing and variable measuring and assessment were used as in **Section 3.1.1.1**. The trial was set out as a randomized complete block with nine treatments (*TABLE 3.3)*.

Table 3.3. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Amount of source	Amount of active ingredient	Method of application
Zn	$ZnSO_4.7H_2O$ (20% Zn)	0.8 g/pot	0.16 g/pot	Soil
B	Boronate (16.5% B)	0.3 g/pot	0.05 g/pot	Soil
Fe	Iron-chelate (6% Fe)	2.0 g/pot	0.12 g/pot	Soil
Mo	$Na_2MoO_4.H_2O$ (39.5% Mo)	0.25 g/l	0.10 g/l	Foliar
Mn	$MnSO_4$ (34% Mn)	0.5 g/pot	0.17 g/pot	Soil
Cu	$CuSO_4.5H_2O$ (25% Cu)	0.2 g/pot	0.05 g/pot	Soil
Spoormix[1]	Various	1.4 g/pot	-	Soil
Control	NA[2]	NA	NA	NA
Gypsum	($CaSO_4$)	1 g/pot	-	Soil

[1]Commercial multi-micronutrient fertiliser (Fe: 53g/kg; Mn: 23 g/kg; Zn: 21g/kg; Cu: 11g/kg; Mo 7g/kg; B: 34 g/kg)

[2]NA – not applicable

The low pH of the soil raised concerns about possible Al toxicity and therefore the gypsum ($CaSO_4$) treatment was included in the trial. Aluminium that is absorbed by plant roots occupy adsorption sites that are reserved for other nutrients. A toxicity of Al is thus an indirect nutrient deficiency of other nutrients. Gypsum in the soil has the capacity to reduce the Al-adsorption by binding with the Al cations (Marschner, 1997). Amounts of nutrients applied in the various treatments were calculated as minimum nutrient levels in the soil (Saayman *pers. comm.*, 1997) needed for optimum plant growth. The amount of Spoormix® was calculated by not exceeding the optimum amount of B (as potentially most toxic nutrient) in the soil. The optimum amount of B in soil is 5 mg/ kg.

3.1.1.3 Sonsbeek nutrient trial

The objective of this trial was to test the growth response of *P. patula* seedlings in pots to various nutrient treatments on a problem soil type from the North Eastern Cape.

The soil was collected from the Ugie District and formed part of the B-horison of the Bloemdal soil form (sandy clay loam texture) with dolerite as the parent material.

Detailed soil analysis is presented in *APPENDIX 2*. The same methods of soil collection, trial preparation, seed sowing and variable measuring and assessment were used as in **Section 3.1.1.1**. The trial was set out as a randomized complete block with nine treatments (*TABLE 3.4)*.

Table 3.4. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Amount of source	Amount of active ingredient	Method of application
Zn	$ZnSO_4.7H_2O$ (20% Zn)	0.8 g/pot	0.16 g/pot	Soil
B	Boronate (16.5% B)	0.3 g/pot	0.05 g/pot	Soil
Fe	Iron-chelate (6% Fe)	2.0 g/pot	0.12 g/pot	Soil
Mo	$Na_2MoO_4.H_2O$ (39.5% Mo)	0.17 g/l	0.07 g/l	Soak seeds
Lime	$CaCo_3.MgCO_3$	3.0 g/pot	-	Soil
Cu	$CuSO_4.5H_2O$ (25% Cu)	0.2 g/pot	0.05 g/pot	Soil
Control	Control	NA	NA	NA
2P	Dubble Supers (22% P)	0.3 g/pot	0.07	Soil
Gypsum	$CaSO_4$	1 g/pot	-	Soil
NPK + lime	2:3:2 (25) + lime	2 g/pot	-	Soil

The amount of lime applied was calculated according to the method of Eksteen (1969), but because of lime induced chlorosis that was observed in the liming trial of **Section 3.1.1.1**, it was decided to reduce the field factor to 2. The amount of N,P and K was calculated as prescribed for commercial plantation fertilisation. For fear of Mo adsorption to Fe oxides and –hydroxides in the soil, the nutrient was applied by means of soaking the seeds in a 25 g $Na_2MoO_4.H_2O$ /1.5 l of water solution for 24 hours. This is accepted maize sowing practice in the Natal Midlands on similar highly weathered, low pH soils.

3.1.1.4 Pasteurisation trial

The objective of this trial was to test the response of *P. patula* seedlings in pots to the pasteurisation of soils and to determine whether soil micro-organisms influence the bacterial preference of potted seedlings to nitrogen source. The effect of mycorrhizae on tree growth was tested by the application of *Rhizopogon rubescens* to the sterilised and unsterilised soil.

The soil came from the same site as the soil used in the Sonsbeek nutrient trial of **Section 3.1.1.3**. Pasteurisation of the soil was done at the University of Stellenbosch through a process were the soil (in 10 kg quantities) was heated to 81 °C for three hours and then left to cool for 24 hours. The same methods of soil collection, trial preparation, seed sowing and variable measuring and assessment were used as in **Section 3.1.1.1**. The trial was conducted as a 2x4 factorial with two N sources and a mycorrhiza treatment being tested at two levels of pasteurisation.

Nitrogen as NH_4^+- source was applied to the soil as $(NH_4)_2SO_4$ (16% N; 24.2% S) at a rate of 120 mg mineral N /kg of soil as recommended by Ortas *et al.* (1996). The NO_3-N source was applied as $NaNO_3$ (16.5% N) at the same rate of mineral N per kg of soil. To compensate for the addition of S with the $(NH_4)_2SO_4$ (16% N; 24.2% S) treatment, $CaSO_4$ was added to the $NaNO_3$ treatment. Treatment details are presented in *TABLE 3.5*. The fruiting bodies of an ectomycorrhizal fungus (*Rhizopogon rubescens)* were collected in a *P. radiata* plantation near Stellenbosch. An inoculant was prepared by grating the fruiting bodies to pulp and adding it as a water solution to the potted soil surface at a rate of 4.5 g dry matter/ m^2 (Theron, *pers. comm. 2000).*

Table 3.5. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Amount of source	Amount of active ingredient	Method of application
NH_4^+-source	$(NH_4)_2SO_4$ (16% N; 24.2% S)	0.975 g/pot	0.156	Soil
NO_3^--source	$NaNO_3$ (16.5% N)	0.945 g/pot	0.156	Soil
	$CaSO_4$	1.004 g/pot	-	Soil
Mycorrhizae	*Rhizopogon rubescens*	4.5 g dry matter/ pot	NA	Soil surface
Control	NA	NA	NA	NA

3.1.1.5 Indicator trial: Cauliflower

The objective of this trial was to test the growth response of cauliflower seedlings to various micronutrient treatments on a soil from the North Eastern Cape and the Western Cape. Cauliflower, being used as an indicator species, shows clear symptoms in regards to Mo and B deficiencies. Typical Mo deficiencies are oversized leaf formation (sweep tail) and colouring of the foliage (Hewitt, 1969; Salisbury and Ross, 1985; Gupta, 1997;

Marschner, 1997). A deficiency in B is apparent as the 'hollow stem disease' that is symptomatic of internal collapse of tissue (Hewitt, 1969; Salisbury and Ross, 1985; Marschner, 1997).

The North Eastern Cape soil came from the same site as the soil used in the Sonsbeek nutrient trial of **Section 3.1.1.3**. The Western Cape soil comes from Jonkershoek and is part of a dark coloured neocutanic B-horison of an Oakleaf soil form (sandy loam texture) of alluvial origin with a non-luvic B-horison and an A-horison that is not bleached. The same methods of soil collection and trial preparation were used as in **Section 3.1.1.1**. Seeds were obtained from a commercial seed outlet in ready-to-sow packs. Three seeds were sown per pot and after germination they were pricked-out to leave a single seedling per pot. Boron was mixed into the soil as boronate (16.5% B) and Mo was applied as a foliar treatment. The Mo treatment was repeated after 8 weeks. Treatment details in *TABLE 3.6*. The trial was set out as a 2x4 factorial with the nutrient treatments being tested at the level of two soil types with 8 pots per treatment.

Table 3.6. *Treatments applied, their sources, amounts and methods of application*

Treatment	Source	Amount of source	Amount of active ingredient	Application
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.25 g/l	0.10 g/l	Foliar
B	Boronate (16.5% B)	0.3 g/pot	0.05 g/pot	Soil
Mo + B	$Na_2MoO_4.H_2O$ (39% Mo) and Boronate (16.5% B)	See above	See above	Foliar (Mo) and soil (B)

The seedlings were grown in a greenhouse at the University of Stellenbosch and harvested at 147 days. At the end of the trial the plants were removed from the pots and the soil washed from the roots. Before harvesting the GLD and the colour of the old and young foliage were measured. The same procedures for colour determination and of drying were followed as in **Section 3.1.1.1**. The dry mass of the above and below ground biomass was measured.

3.1.1.6 Indicator trial: Soya

The objective of this trial was to test the growth response of soya seedlings to various nutrient treatments on a soil from the North Eastern Cape. Soya was chosen due the

relative ease of visual nutrient deficiency diagnosis in a broadleaf species. A suspected imbalance in the N nutrition on the particular soil was best investigated by use of a leguminous nitrogen fixer (Marschner, 1997).

The soil came from the same site as the soil used in the Liming trial of **Section 3.1.1.1** and the same methods of soil collection and trial preparation were used. Soya seed were acquired from the Agronomy Department at the University of Stellenbosch. Three seeds were sown per pot and after germination, the seedlings were reduced to one per pot. The trial was set out as a randomized complete block with eight treatments (*TABLE 3.7).*

Table 3.7. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Amount of source	Amount of active ingredient	Method of application
Zn	$ZnSO_4.7H_2O$ (20% Zn)	0.8 g/pot	0.16 g/pot	Soil
B	Boronate (16.5% B)	0.3 g/pot	0.05 g/pot	Soil
Fe	Iron-chelate (6% Fe)	2.0 g/pot	0.12 g/pot	Soil
Mo	$Na_2MoO_4.H_2O$ (39.5% Mo)	0.25 g/l	0.10 g/l	Foliar
Mn	$MnSO_4$ (34% Mn)	0.5 g/pot	0.17 g/pot	Soil
Cu	$CuSO_4.5H_2O$ (25% Cu)	0.2 g/pot	0.05 g/pot	Soil
Spoormix	Various	1.4 g/pot	-	Soil
Control	NA	NA	NA	NA

After 119 growing days the trial was terminated and the following variables measured: total height of plants, height of first branch and stem diameter just under the cotyledon scar. The plants were removed from the pots and then washed to remove soil and oven-dried at 70 °C for 24 hours. The mass of the roots, stems, foliage and pods were determined and then analysed.

3.1.2 Field trials

3.1.2.1 Field plantings: Ludano

The objective of this trial was to test the growth of *P. patula* seedlings under field conditions to various micronutrient treatments and a gypsum treatment. This trial was part of a soil cultivation trial (pitting, scalping, augering, ploughing and ridging) established by North East Cape Forest (NECF) research staff during December 1997.

The trial was situated on the farm Ludano (B04) in the Maclear District. The soils in the trial area are mostly red, apedal dystrophic with the dominant soil forms being Hutton of fine sand loam texture (detailed chemical analysis in *APPENDIX 2)*. The lithology varies from sandstone to dolerite with an effective rooting depth of 120-150 cm. In the A-horison the clay content varies between 15-35 % and in the B-horison between 25-50 %. The seedlings were acquired from the NECF Ugie nursery in Unigro 128 containers. The seedlings were planted in December 1998 according to accepted planting methods with a polymer superabsorbent (1g superabsorbent in 2 l of water per tree) and watered on the day of planting. No fertiliser was applied in the trial.

The trial was set out as a 5x6 factorial in four replications with both treatments (cultivation and nutrient) being randomized throughout the trial. The nutrient treatments were applied as described in *TABLE 3.8.* Six seedlings were planted to a plot a an 2.74 m x 2.74 m espacement. The cultivation treatments were the following:

(i) Manual pitting: pits dug with mattock and seedling planted with a trowel.

(ii) Scalping: topsoil removed and seedlings planted in B-horison.

(iii) Ridging: topsoil collected to one side and seedlings planted on the ridge.

(iv) Disc ploughing: total soil preparation.

(v) Mechanical pitting: planting pit dug with pitting head (augering).

Table 3.8. *Treatments applied, their sources, amounts and methods of application.*

Treatment	**Source**	**Concentration**	**Amount of source**	**No of trees**	**Application**
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.25 g/l	NA	120	Foliar
B	Boronate (16.5% B)	NA	1.5 g/ tree	120	Soil
Fe	Fe Na EDTA chelate	NA	5 g/ tree	120	Soil
Mo+B+Fe	$Na_2MoO_4.H_2O$ (39% Mo) + Boronate (16.5% B) + Fe Na EDTA chelate	See above (Mo)	See above (B +Fe)	120	Foliar (Mo), soil (B), soil (Fe)
Gypsum	$CaSO_4.7H_2O$	NA	38 g/tree	120	Soil
Control	NA	NA	NA	120	NA

The B and Fe treatments were applied by means of a water solution and the gypsum was mixed into the soil before the seedlings were planted. The Mo was applied by foliar means.

Six months after nutrient application height (Ht) and ground line diameter (GLD) of the seedlings were measured and stress and mortality assessed. The degree of weed competition was estimated on a scale of 1 to 3 (1- no competition; 3- severe weed competition) for each seedling.

3.1.2.2 Field plantings: Sonsbeek

The objective of this trial was to test the response of *P. patula* seedlings to various micronutrient treatments under field conditions.

The trial was situated in an experimental trial block on the farm Sonsbeek (G32b) in the Ugie District. The soil in the area is of the Bloemdal form (orthic A/red apedal B/ unspecified with signs of wetness) with a sandy clay loam texture and dolerite as the parent material. The clay content in the A-horison is 20% and increases in the B-horison to 35-40%. There is no visible restriction in rooting depth although wetness appears at 1300 mm. A detailed soil analysis appears in *APPENDIX 2*.

The trial was set out as a randomized complete block with five treatments (*TABLE 3.9)* in four replications. The seedlings used in the trial came from the NECF Ugie nursery in Unigro 128 containers and were planted in December 1998 according to accepted planting methods with a polymer superabsorber. The seedlings were watered on the day of planting. No fertiliser was applied. Eight seedlings were planted per replication at an espacement of 1333 sha.

Table 3.9. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Amount of source	Amount of active ingredient	Application
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.25 g/l	0.10 g/l	Foliar
B	Boronate (16.5% B)	1.5 g/ tree	0.25 g/tree	Soil
Fe	Fe Na EDTA chelate (6% Fe)	5 g/ tree	0.3 g/tree	Soil
Cu	$CuSO_4.5H_2O$ (25% Cu)	0.5 g/tree	0.125 g/tree	Soil
Zn	$ZnSO_4.7H_2O$ (20% Zn)	1.5 g/tree	0.3g tree	Soil
Control	NA	NA	NA	NA

3.1.2.3 Tree evaluation: Ludano

The objective of this trial was to test the response of poorly growing and moribund *P. patula* stands (4 years old) to various micronutrient treatments over the period of one growing season under field conditions. The area for the trial was identified by research staff at NECF.

The trial was situated in Compartment B01 on the farm Ludano near Maclear. The trial plots were contained in an area where typical growth deficient symptoms and abnormalities are encountered. The soils in the area are mainly red apedal dystrophic soils of the Hutton soil form (sandy clay loam texture). Effective rooting depth is greater than 1500 mm with the clay percentages in the A-horison varying between 20-25% and in the B-horison between 30-35%. A detailed soil analysis is presented in *APPENDIX 2* The compartment was previously cropped with maize.

The trial was a randomized complete block with five treatments in four replications. Ten trees in the tree line comprised one treatment. Nutrient treatments (*TABLE 3.10)* were applied to the foliage by means of 20 l knapsacks. A wetting agent (**Effekto G-49**) was added to ease foliar absorption of nutrients. The whole tree was sprayed and to prevent drift contamination, a buffer row was left between treated tree rows.

Table 3.10. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Concentration	Amount of active ingredient	Application
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.25 g/l	0.10 g/l	Foliar
B	Boronate (16.5% B)	2.5 g/l	0.41 g/l	Foliar
Fe	Fe Na EDTA chelate (6% Fe)	3 g/l	0.18 g/l	Foliar
Mo+B+Fe	$Na_2MoO_4.H_2O$ (39% Mo) + Boronate (16.5% B) + Fe Na EDTA chelate	See above	See above	Foliar
Control	NA	NA	NA	NA

At the time of nutrient application the diameter (dbh) and height of the treated trees were measured and tree condition evaluated. The evaluation was based on a system used by Birk (1991) to assess growth and form of deformed *P. radiata* trees growing on former pastures. The defects of the trees were grouped into three major types:

(i) Leader defects: forks, multiple leaders and damage to the leaders

(ii) Stem defects: lean, butt sweep, kinks and sinuosity

(iii) Branch defects: branch form and straightness

Similar types of tree evaluation systems have been used by Hopmans and Flinn (1984), Ellis and Wiese (1997) and Fyfield *et al.*(1998). In addition, general tree health was assessed by classification of each tree in four colour categories:

(i) Green

(ii) Minimum yellow

(iii) Medium yellow

(iv) Yellow

The Munsell colour card system was used as a further indicator of foliage colour. Colour was measured of needles that were exposed to the sun on the northern side of the tree. Needles at breast height were selected and if differences between the adaxial and abaxial surfaces were noticed, both were measured. The colour of the needles was measured on the body of the leaf. Although Grey *et al.* (1979) found better correlation between foliage colour measured at the base of the tree and tree performance than with colour measured on the body of needles, the correlation was minimal (R^2 = 0.19) and was based on the individual components of the Munsell system and not as a colour value on the whole. The various variables were all used to evaluate overall tree condition and to place the tree into one of three categories (i) good, (ii) medium and (iii) bad.

At the end of the trial foliar samples were taken from each tree, bulked into two replications of the various treatments and analysed. This was done to assess whether the foliar application of the nutrients was successful and that the needles absorbed some of the nutrients.

3.1.2.4 Tree evaluation: Riverside

The objective of this trial was to the test the response of growth deficient *P. patula* stands (seven years old) to various micronutrient treatments over the period of one growing season under field conditions. Research staff at NECF identified the trial area.

The trial was situated on the farm Riverside, Maclear, Compartment D08. Seedlings planted in this particular area have been subjected to severe mortality and replanting was necessary on several occasions. Subsequent growth was below par and a large percentage of the trees were deformed and of poor quality. The area was previously cropped with maize. The soils in the area are mainly red apedal dystrophic soils of tillite lithology and of the Hutton soil form. The effective rooting depth is greater than 1500 mm with a clay content in the A-horison of 30% and in the B-horison of 40%. Fe and Mn concretions are common throughout the soil profile. A detailed soil analysis is presented in *APPENDIX 2*.

Five nutrient treatments (*TABLE 3.10*) were randomized in a three replication randomized complete block. Ten trees in the tree line comprised one treatment and nutrients were applied to the trees by means of 20 l knapsacks. To prevent nutrient drift contamination a buffer row was left between the treated rows.

The evaluation and measurement of the trees and tree health was done in the same way as in **Section 3.1.2.3**. At the end of the trial foliar, samples were taken from each tree, bulked into two replications of the various treatments and analysed. This was done to assess whether the foliar application of the nutrients was successful and that the needles absorbed some of the nutrients.

3.1.2.5 Tree evaluation: Feltham

The objective of this trial was to test the growth response of five year old growth deficient *P. taeda* stands to various micronutrient treatments over the period of one growing season under field conditions. Research staff at NECF identified the area of the trial.

The trial was located at Feltham farm, Ugie, at compartment C17B. The soils in the area are typically red apedal, dystrophic soils with Hutton (dominant) and Clovelly soil forms. The lithology is sandstone/ tillite mixture with clay in the A-horison between 20-30% and the clay in the B-horison between 25-40%. The effective rooting depth is greater than 1500 mm.

The trial was set out as a randomized complete block in three replications with five treatments. The application of the nutrient treatments was similar to the treatments applied in **Section 3.1.2.3** with details in *TABLE 3.10*. The measurement and evaluation of the trees and tree conditions are the same as in **Section 3.1.2.3**. At the end of the trial foliar samples were taken from each tree, bulked into two replications of the various treatments and analysed. This was done to assess whether the foliar application of the nutrients was successful and that the needles absorbed some of the nutrients.

3.2 Natal Midlands trials

3.2.1 Field plantings: Giants Castle

The objective of this trial was to test the growth of *P. patula* seedlings under field conditions to various micronutrient treatments and a gypsum treatment. The trial was established partly on old lands and partly on virgin grasslands.

The trial was situated in a trial plot on the Giants Castle Estate near Mooi River in the Natal Midlands. The soils are red, dystrophic of the Hutton soil form and derived from a dolerite parent material. The clay percentage in the A-horison varies around 20% and in the B-horison it increases to 35-40%. Although stones are present in the profile, they occur on a limited scale and present no obstruction to root growth. A detailed soil analysis appears in *APPENDIX 2.* The seedlings were acquired from the Mondi Mountain Home Nursery in Hilton in Unigro containers. The seedlings were planted in May 1998 according to accepted planting methods with a polymer superabsorbant and watered on the day of planting. No fertiliser was applied in the trial.

The trial was set out as a 2x6 factorial of six nutrient treatments on a virgin grassland soils and an old land soil (previously cropped with maize). There were eight trees per treatment in three replications. Treatment details are presented in *TABLE 3.11*. The gypsum was mixed into the soil before the seedlings were planted.

Table 3.11. *Treatments applied, their sources, amounts and methods of application.*

Treatment	Source	Concentration	Amount of active ingredient	Application
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.25 g/l	0.10 g/l	Foliar
Mo	$Na_2MoO_4.H_2O$ (39% Mo)	0.15 g/tree	0.06 g/tree	Soil
B	Boronate (16.5% B)	2.5 g/l	0.41 g/l	Foliar
B	Boronate (16.5% B)	0.2 g/tree (10-15 kg/ha)	0.03 g/tree	Soil
Mo+B+ gypsum	$Na_2MoO_4.H_2O$ (39% Mo) + Boronate (16.5% B) + gypsum	Mo and B (see above), gypsum: 38 g/tree (2% solution)	See above	Foliar (Mo) + Soil (B and gypsum)
Control	NA	NA		NA

Seven months after the seedlings were planted, the height and GLD were measured. Due to unscrupulous weeding on the old land part of the trial, that section of the trial had to be aborted.

3.2.2 Tree evaluation: Harleigh

The objective of this trial was to test the response of poorly growing *P. patula* stands to various micronutrient treatments over the period of one growing season under field conditions. The site for the investigation was identified by staff at the Mondi South Head Office.

The trial was situated on the farm Harleigh near Mooi River. Seedling mortality, stem deformities and poor growth were encountered on the site. The soils are dominated by the Hutton soil form of dolerite origin. The clay percentage in the A-horison is 40% and in the B-horison between 45 and 50%. There are no root barriers in the typically red, apedal soil that is common of the area. The detailed soil analysis appears in *APPENDIX 2.*

The layout of the trial and application of treatments are similar to the trial in **Section 3.1.2.3.** Trees were measurement and assessed as in **Section 3.1.2.3**. Foliar samples were collected from healthy and unhealthy trees and analysed.

3.3 Mpumalanga trials

3.3.1 Pot trial

The objective of this trial was to test the growth response of *P. patula, P. elliottii, P. taeda, P. greggii* and *Eucalyptus nitens* seedlings to various micronutrient treatments, with and without the addition of lime on soil from Mpumalanga.

The soil was collected from the B-horison of a Hutton soil in the Graskop area on the London Estate. The B-horison forms part of a Hutton soil form with a sandy loam texture. The soils in the area are of dolomite origin. The detailed soil analysis is given in *APPENDIX 2*.

The collection of soil and preparation of the trial at the University of Stellenbosch was done in similar fashion to the liming trial of **Section 3.1.1.1**. The same treatments in the same amounts were applied to the pots (*TABLE 3.2*), with the exception of the lime that was applied to the soil in an amount that was calculated from the method of Eksteen (1969) using a field factor of 2.

The trial was run for 758 days during which time the height growth, diameter growth and colour changes were measured and monitored. The assessment of variables at the end of the trial was done as in **Section 3.1.1.1**.

3.3.2 Field trials

3.3.2.1 Tree evaluation: London

The objective of this trial was to test the response of growth deficient *P. patula* stands to various micronutrient treatments over the period on one growing season under field conditions. Staff at the Mondi Driekop Estate identified the area for the investigation.

The sites for the trial was located near Graskop, compartment G17, London. Tip dieback, mortality and severe colouring of the foliage occurs at the end of the dry season and

nutrient deficiencies were observed. Some of the trees were sampled and the foliage sent for analysis (*APPENDIX 1*). The soils in the area are classified as the Hutton and Griffin soil forms. The clay percentage in the A-horison varies between 25-30% and in the B-horison between 30-35%. A detailed soil analysis is presented in *APPENDIX 2*. The effective rooting depth is greater than 1500 mm.

The trial was designed as a randomized complete block. Five nutrient treatments in four replications were applied to the ten trees in a single tree line treatment. The nutrient treatments (*TABLE 3.10*) were applied with 20 l knapsacks. A wetting agent (**Effekto G-49**) was added to the nutrient solutions to aid absorption by the foliage. The whole tree was sprayed and to prevent drift contamination between the trees, a buffer row was left between the treated tree rows.

The diameter and height of the treated trees were measured and the health and condition of the trees were evaluated by the system used in **Section 3.1.2.3**. The colour of the foliage was assessed in the same way as described in **Section 3.1.2.3**. The application of the nutrients and first measurement and assessment of the trees were done in May 1999. At the end of the dry season (early August) the trees were again measured and assessed. Foliar samples were taken from healthy and unhealthy trees and analysed.

3.3.2.2 Tree evaluation: Berlin P3

The objective of this trial was to test the response of moribund *P. elliottii* stands to various micronutrient treatments over the period of one growing season under field conditions. Staff from SAFCOL head office in Nelspruit identified the site for the trial.

The trial was located in Berlin State Forest (compartment P3), near Kaapsche Hoop. Poor tree form with chlorotic and/or necrotic needles was widely spread throughout the compartment. Current year foliage over the whole tree was chlorotic. Trees of severe chlorosis and apparently healthy trees were selected for comparative foliar analyses. The soils in the area are of dolomite/limestone parentage with chert pebbles and small rocks on the surface. Mn concretions were visible throughout the soil profile. The soils are of

the Hutton soil form with a sandy clay loam texture. Effective rooting depth was greater than 1500 mm.

The trial was set out as a randomized complete block in three replications with five treatments. The application of the nutrient treatments was the same as the treatments applied in **Section 3.1.2.3** with details in *TABLE 3.10.* The nutrients were applied, trees measured and tree health/condition assessed in May 1999 and final assessment was after the winter in August 1999. The measurement and evaluation of the trees and tree conditions were the same as in **Section 3.1.2.3**.

3.3.2.3 Tree evaluation: Berlin G17

The objective of this trial was to test the response of poorly growing *P. patula* stands to various micronutrient treatments over the period of one growing season under field conditions. The site for the trial was identified by staff from SAFCOL head office in Nelspruit.

The trial was in situated near Kaapsche Hoop, Berlin State Forest, compartment G17. The soils in the area are similar to the soils described in **Section 3.3.2.2** with the same lithology. Foliage samples were taken of yellow and poor growth trees and also of healthier, greener trees. There seemed to be no pattern of chlorosis but only the needle tips were necrotic. Chlorosis was observed on both the bottom and top half of the trees. The trees in the area of general poor quality with severe colouring during winter. The soils are of the Hutton soil form (sandy clay loam texture) with an effective rooting depth greater than 1500 mm. Small surface stones and chert are scattered around the area. Manganese concretions are visible in the soil profile.

The trial was set out as a randomized complete block in three replications with five treatments. The application of the nutrient treatments was the same as the treatments applied in **Section 3.1.2.3** with details in *TABLE 3.10.* The nutrients were applied, trees measured and tree health/condition assessed in May 1999 and final assessment was after the winter in August 1999. The measurement and evaluation of the trees and tree conditions were the same as described in **Section 3.1.2.3**.

3.4 Western Cape trial

The objective of this trial was to test the growth response of *Pinus patula, P. elliottii, P. taeda, P. greggii* and *Eucalyptus nitens* to various micronutrient treatments, with or without the addition of lime, in pots on a soil from the Western Cape.

The Western Cape soil came from Jonkershoek and is part of a dark coloured neocutanic B-horison of an Oakleaf soil form (orthic A/ neocuttanic B/ unspecified) (sandy loam texture) of alluvial origin. The B-horison is non-luvic and the A-horison is not bleached. The same methods of soil collection and trial preparation were used as in **Section 3.1.1.1**. Seeds from the same seed sources were used and after 375 days the trial was terminated. Measurements and assessments of tree growth and tree conditions were then done. At the end of the trial the final assessment was done on all variables, as in **Section 3.1.1.1**.

4. Results

The results of the various trials are discussed as per region of investigation. Differences between treatments were deemed significant at a p-value < 0.05. The Studend-Newman-Keuls test is used for multiple comparison of treatment means where treatment differences were apparent. The Chi-square test of independence was used for analyses of categorical data to determine treatment effects.

4.1 North Eastern Cape trials

4.1.1 Pot trials

4.1.1.1 Liming trial

The effect of increased pH of the soil through liming was observed as chlorosis on all the lime treated seedlings. Measurement of the soil pH for all treatments showed that the use of a field factor of 4 in the equation of Eksteen (1969) (*EQUATION 3.1)* overestimated

the need for lime and a possible Fe deficiency was induced, a situation commonly developed in forest nurseries (Lyle, 1969; Nakos, 1979; Ellis, 1999). The pH of the limed soil was measured as 6.25 in comparison to the pH of the unlimed soil of 4.67. This was visually diagnosed by chlorosis of young foliage in the lime treated seedlings. The measurement of colour on Day 142 confirmed this with a low p-value (p= 0.0001) (*TABLE 4.1)* that signifies statistical differences between treatments with and without the addition of lime.

Table 4.1. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil. Variables are described below.*

Source	G2	G3	H1	H2	H3	Root	Above	Stem	Needle	Total	BI	Colour
Spp	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002
Lime	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Treat	0.0414	0.0038	0.0010	0.0008	0.0136	0.0685	0.0015	0.0263	0.0043	0.0159	0.0032	0.2451
Spp*Treat	0.0324	0.0018	0.0020	0.0007	0.0115	0.1155	0.0002	0.0181	0.0026	0.0032	0.0007	0.1456
Lime*Treat	0.3273	0.9443	0.0224	0.0009	0.2038	0.2836	0.1137	0.5289	0.0490	0.0689	0.1065	0.2758
Spp*Lime	0.0001	0.0001	0.0016	0.0050	0.0004	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.6572
Spp*Lime*Treat	0.0024	0.0012	0.7268	0.0269	0.0245	0.0357	0.0062	0.2378	0.0144	0.0023	0.0028	0.9463
CV (%)	8.3	9.2	11.3	7.1	6.2	5.6	6.3	9.1	5.5	8.7	7.5	5.7

G: ground line diameter of seedlings measured in mm

H: seedling height measured in mm

G1: ground line diameter measured at period one

H3: seedling height measured at period three

Root/ Above/ Stem/ Needle/ Total: mass of plant parts measured in grams

BI: biomass index

Colour: colour of the needles measured with the aid of Munsell colour charts

There were significant three factor interactions between the different species, the effect of lime and the various treatments for most of the variables (*TABLE 4.1).* It was thus sensible to simplify the interaction by analysis of the lime x treatment seperately for each species. The resultant p-values for analysis by species (*TABLE 4.2)* showed that lime addition had the greatest effect on the growth of the seedlings in that the seedlings that

had received lime, were stunted. This is the case for almost all variables that were measured. There was limited interaction between the effect of liming and the nutrient treatments for all species except for *P. taeda.*

The effect of the lime can be seen in *FIGURE 4.1* where seedlings grown on the limed soil were outperformed by seedlings that were grown on unlimed soil. The reaction to all measured variables of all the species were similar for the application of lime with significant statistical differences ($p<0.0001$) between seedling growth on lime and unlimed soils.

Table 4.2. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil for analysis by species.*

Spp	Source	G1	G2	G3	H1	H2	H3	Root	Above	Stem	Leaf	BI	Total
P. greggii	**Lime**	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	0.1548	0.0708	0.6905	0.0051	0.0131	0.4271	0.0084	0.0449	0.0421	0.1548	0.1374	0.0453
	Lime*Treat	0.7393	0.122	0.1147	0.2095	0.0579	0.8252	0.103	0.1787	0.2152	0.2485	0.2335	0.1426
P. patula	**Lime**	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	0.6301	0.9938	0.3865	0.0145	0.0012	0.085	0.7703	0.1574	0.3007	0.227	0.1083	0.4637
	Lime*Treat	0.5175	0.1464	0.2771	0.1084	0.0045	0.0699	0.3539	0.0599	0.1039	0.0858	0.0882	0.1397
P. elliottii	**Lime**	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	0.0016	0.4336	0.4263	0.1713	0.0628	0.9022	0.6529	0.8608	0.7868	0.8311	0.5002	0.9451
	Lime*Treat	0.7281	0.2933	0.1959	0.3467	0.2864	0.0938	0.2691	0.9345	0.7696	0.9947	0.3181	0.8046
P. taeda	**Lime**	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	0.3844	0.032	0.1968	0.5574	0.6812	0.2858	0.1608	0.023	0.3572	0.0106	0.0104	0.0022
	Lime*Treat	0.1685	0.005	0.0004	0.0612	0.0624	0.0107	0.1274	0.0006	0.1197	0.0047	0.0017	0.0001
E. nitens	**Lime**	.	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	.	.	0.6905	0.042	0.0248	0.0107	0.4899	0.3523	0.4482	0.6417	0.1563	0.545
	Lime*Treat	.	.	0.1147	0.3281	0.0537	0.0408	0.1692	0.2241	0.1757	0.2296	0.0493	0.1710

There was only limited significant differences for treatment effects (*TABLE 4.2).* The greatest response to nutrient addition was for *P. greggii.* Treatment differences were significant for H1 ($p=0.0051$), H2 ($p=0.0131$), root ($p=0.0084$), stem ($p=0.0451$), above ground biomass ($p=0.0449$) and total biomass ($p=0.0453$). Above and below ground biomass nutrient treatments and lime differences for *P. greggii* is shown in *FIGURE 4.1.*

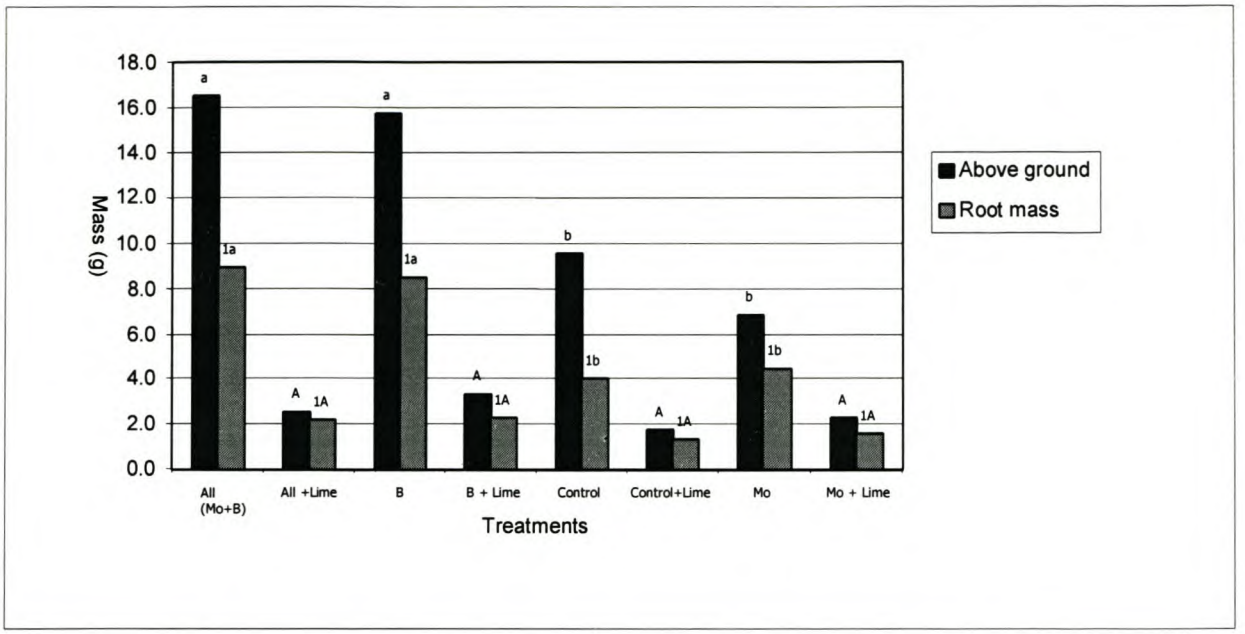


Figure 4.1. *The effect of lime and nutrient applications on plant mass of* P.greggii *seedlings (547 days old). Different letters are regarded as statistically significant. (letters in small caps denote lime addition treatments that were analysed separately from the treatments without lime).*

The All and B nutrient treatments were the best performers (SNK-multiple comparison test). On the lime treated soils the growth effects of the treatments were not as pronounced as on the unlimed soil for *P. greggii.* This illustrates the concept of the Law of Minimum where plant growth is dependent on the nutrient present in the least quantity or with the lowest absorption capacity. Multiple imbalances were thus created with the over-liming of the soil and the greatest demand by the seedlings was for Fe (visually diagnosed Fe deficiency). This situation is commonly found in nursery soil were the addition of lime induces a Fe deficiency.

There was a large difference between the growth rate of the various species. To eliminate the confounding of the liming effect it was possible to analyse the interaction between species and treatments with and without the addition of lime (*TABLE 4.3*). In the no-lime treatment there was limited interaction between species and treatments. The differences between the main effects were thus useful.

Table 4.3. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil for analysis by the liming effect.*

Liming	Source	G1	G2	G3	H1	H2	H3	Root	Above	Stem	Leaf	BI	Total
Lime	Spp	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	0.1452	0.9818	0.2996	0.4252	0.5159	0.0505	0.2696	0.1274	0.1673	0.2027	0.0722	0.1807
	Spp*treat	0.0115	0.0007	0.0074	0.1228	0.0029	0.0029	0.4814	0.5066	0.3998	0.7079	0.0302	0.4826
No lime	Spp	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Treat	0.0087	0.0264	0.0010	0.0001	0.0001	0.0099	0.0889	0.0013	0.0121	0.0032	0.016	0.0139
	Spp*treat	0.7556	0.0774	0.1761	0.2618	0.0106	0.1713	0.1518	0.0676	0.4245	0.0262	0.0283	0.0699

In *TABLE 4.4* differences between the growth performance of the various species are apparent. There was a meaningful difference between the best growth of *P. elliottii* and *P. taeda* to the growth of *E. nitens* that is slightly better than the growth of *P. greggii* and *P. patula*.

Table 4.4. *Mean values of various variables made from the growth measurements on the pot trial of the North Eastern Cape soil for the different species. Different letters indicate differences between the means.*

Species	No lime					Lime				
	Total	**BI**	**Root**	**Above**	**Stem**	**Total**	**BI**	**Root**	**Above**	**Stem**
P. elliottii	42.31^{a}	11045^{a}	13.63^{a}	29.17^{a}	15.44^{a}	12.97^{a}	1705^{a}	5.00^{a}	7.97^{a}	3.31^{a}
P. taeda	33.20^{b}	7498^{b}	11.75^{a}	24.82^{b}	12.21^{b}	8.70^{b}	1075^{b}	3.10^{b}	5.61^{b}	2.25^{b}
E. nitens	18.80^{b}	3409^{a}	4.87^{b}	14.25^{c}	7.78^{c}	10.11^{b}	1469^{a}	2.14^{b}	7.97^{a}	3.41^{a}
P. greggii	15.72^{c}	1924^{cd}	6.51^{b}	10.06^{d}	5.04^{d}	4.32^{c}	251^{c}	1.85^{b}	2.47^{c}	0.85^{c}
P. patula	14.30^{c}	1102^{d}	5.80^{b}	9.21^{d}	3.05^{d}	4.07^{c}	141^{c}	2.16^{b}	1.90^{c}	0.55^{c}

There were more variables (G1, G2, G3, H2, and H3) that interact between the species and the treatments for the lime treatment. For the other variables investigations of the main effects were possible and differences between the species are apparent ($p<0.0001$) (*TABLE 4.3*). No differences were found for the nutrient treatments on the limed soil. The application of nutrients to the seedlings growing on the unlimed soil however proved to be beneficial. There were statistical differences for all the variables (except Root, $p=0.0889$). The SNK-mulptiple comparison procedure (*TABLE 4.5*) show that the B

treatment performed significantly better than the Control treatment for variables BI and Above. A probable Mo-toxicity was cause for the Mo treatment performing on average lower than the Control treatment and significantly lower than the B treatment.

Table 4.5. *Mean values of various variables made from the growth measurements on the pot trial of the North Eastern Cape soil for the nutrient treatments. Different letters indicate differences between the means.*

Treatment	No lime					Lime				
	Total	**BI**	**Root**	**Above**	**Stem**	**Total**	**BI**	**Root**	**Above**	**Stem**
All	23.66^{ab}	6305^{a}	9.27^{a}	17.62^{ab}	8.28^{ab}	7.78^{a}	907^{a}	2.66^{a}	5.46^{a}	2.06^{a}
B	27.94a	5287^{a}	8.79^{a}	20.55^{a}	9.97^{a}	8.81^{a}	1047^{a}	3.34^{a}	5.12^{a}	2.17^{a}
Mo	18.69^{b}	3297^{b}	6.87^{a}	12.55^{c}	7.49^{b}	8.61^{a}	1053^{a}	2.83^{a}	5.79^{a}	2.20^{a}
Control	24.36^{ab}	5087^{a}	8.76^{a}	16.12^{bc}	8.96^{ab}	6.93^{a}	705^{a}	2.57^{a}	4.37^{a}	1.74^{a}

4.1.1.2 Ludano nutrient trial

There was an initial difference in seedling growth for the first measurements of height and ground line diameter between the nutrient treatments. In time this difference became insignificant and with biomass determination there was no significant differences between the various nutrient treatments (*TABLE 4.6*).

Table 4.6. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil.*

Source	H1	G1	H2	G2	H3	G3	Total	Root	Above	Leaf	Stem
Treat	0.0337	0.0009	0.0016	0.0016	0.2643	0.0706	0.2229	0.1938	0.1709	0.1978	0.1420
CV (%)	9.3	11	10.1	8.3	7.2	8.1	12.3	11.5	13.1	12.7	12.9

For the first measurement (H1 and G1) the Cu treated seedlings performed significantly better that the Lime and Control seedlings, but not significantly better than the seedlings

of the other treatments. The Cu treated seedlings as best entry was also observed for H2 (p=0.0016) and G2 (p=0.0016) (*TABLE 4.7*).

The seedlings of the Cu, Fe and Control treatments had the highest average biomass values, but because of variation within treatments (and thus a resultant high coefficient of variation) there was no indication of significant treatment differences.

No difference in foliage colour was observed between the seedlings of the different treatments. There was a uniformly green colour between the older and the younger foliage.

Table 4.7. *Average values for various variables from growth measurements made on the pot trial of the North Eastern Cape soil. Different letters indicate significant differences.*

Treatment	G1	H1	G2	H2	G3	H3	Total	Above	Root
Cu	1.40[a]	60.6[a]	1.58[a]	74.9[ab]	2.87[a]	101.3[a]	3.61[a]	1.72[a]	1.89[a]
Fe	1.36[ab]	52.1[ab]	1.39[ab]	55.8[b]	2.49[a]	100.0[a]	3.83[a]	1.86[a]	1.97[a]
Zn	1.34[ab]	48.9[b]	1.34[ab]	55.0[a]	2.12[a]	77.1[a]	2.46[a]	1.05[a]	1.41[a]
Mo	1.12[ab]	44.7[ab]	1.21[b]	44.9[b]	2.11[a]	89.3[a]	2.72[a]	1.28[a]	1.44[a]
Spoormix	1.11[ab]	45.0[ab]	1.13[b]	47.6[b]	1.78[a]	80.7[a]	2.32[a]	1.18[a]	1.14[a]
Mn	1.10[ab]	44.2[ab]	1.14[b]	50.5[a]	2.30[a]	80.0[a]	2.60[a]	1.11[a]	1.49[a]
B	1.10[ab]	46.6[ab]	1.05[b]	48.5[b]	1.98[a]	79.2[a]	2.02[a]	0.95[a]	1.07[a]
Lime	1.09[b]	49.7[ab]	1.25[b]	53.6[b]	1.97[a]	88.6[a]	2.39[a]	1.28[a]	1.15[a]
Control	1.08[b]	49.8[ab]	1.22[b]	59.8[b]	2.06[a]	85.0[a]	3.33[a]	1.84[a]	1.50[a]

4.1.1.3 Sonsbeek nutrient trial

There was a distinct and significant visual growth reaction to the application of nutrient treatments. This was supported by statistical analyses and $p<0.0001$ was found for all measured variables. The application of Zn, Cu, lime and gypsum did not increase the growth of the seedlings to a level significantly greater than the control seedlings (*FIGURE 4.2*). As single application these nutrients are thus regarded as ineffective.

The best growth performance (for most variables) was observed for the NPK treated seedlings. The growth of these seedlings was significantly better than the seedlings of the control treatment. The growth of the NPK treated seedlings were however not significantly different for most variables than the seedlings treated with B, Fe, Mo or P

(*FIGURE 4.2*). The limited distinction between the seedlings grown with only the application of single nutrients (B, Fe, Mo and P) and a complete fertiliser application (NPK 2:3:2 (22)) is an indication of possible deficiency of any one or combination of these nutrients in the soil.

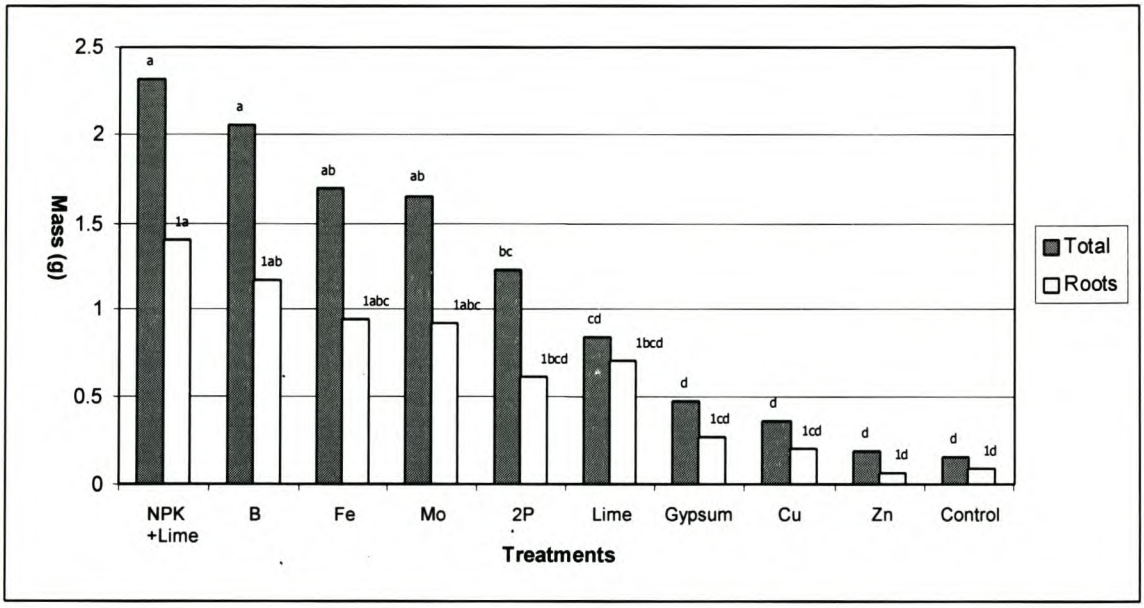


Figure 4.2 *The effect of nutrient application to* P. patula *seedlings on biomass. Different letters indicate treatmentsthat are statistically significant at the 5% level.*

4.1.1.4 Pasteurisation trial

The p-values (*TABLE 4.8*) show that there was no interaction ($p>0.05$) between the treatments and the sterilization of the soil. Interpreting the main effects of the trial was thus possible.

Table 4.8. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil.*

Source	H1	G1	BI	Total	Above	Needles	Stem	Root
Past	0.8990	0.7971	0.5685	0.5450	0.5388	0.6501	0.2972	0.5626
Treat	0.0218	0.0197	0.0109	0.0263	0.0206	0.0156	0.0475	0.0420
Pas*Treat	0.7309	0.7740	0.9484	0.8153	0.7896	0.7380	0.8280	0.8308
CV (%)	3.4	4.5	4.9	3.7	2.4	2.5	4.1	5.6

There is no effect of soil pasteurisation on the growth of the seedlings ($p>0.05$ for all variables). The addition of the various treatments did however influence seedling growth with $p<0.05$ for all variables measured. From *FIGURE 4.4* it can be seen that the seedlings that grew with the aid of mycorrhizae were the best performers. The oldest needles of all the seedlings without the mycorrhizae treatment turned a purple hue (5PR5/2) after Day 80. This is symptomatic of a P deficiency (*FIGURE 4.3*).

Figure 4.3. *P deficiency in a pine seedling (left) is apparent on the older foliage that has turned a purple hue (5PR5/2). The addition of* Rhizopogon rubeccens *to the seedling grown on the same soil (right) increased P absorption and no deficiencies were observed.*

The effect of added N did not statistically influence the growth of the seedlings although on average the NO_3-N source did have a positive influence on seedling growth. The seedlings with the soil added $(NH_4)_2SO_4$ grew below average and were the worst performers.

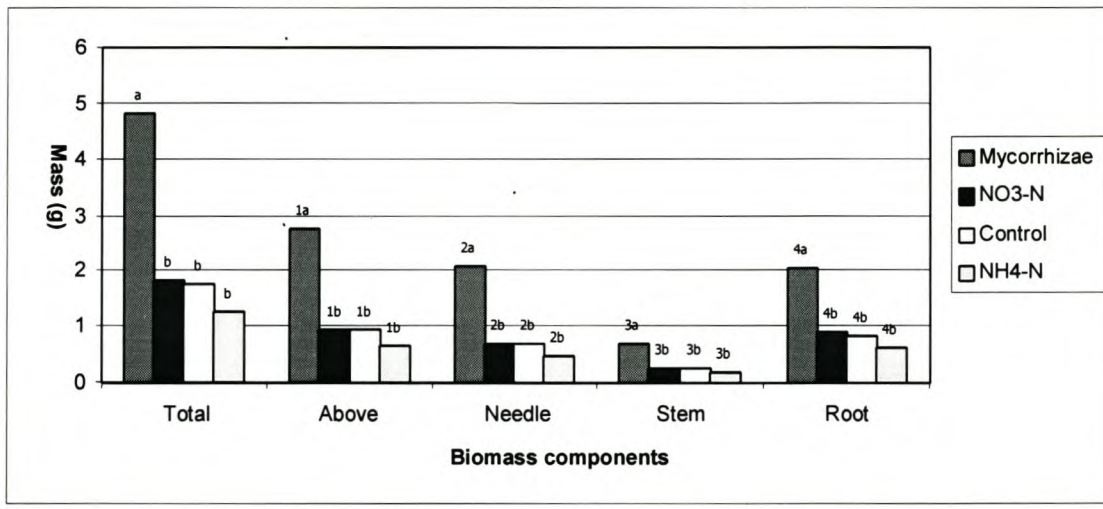


Figure 4.4. *Treatment differences in the pasteurisation trial for various variables. Different letters signify statistical differences.*

4.1.1.5 Indicator trial: cauliflower

The p-values acquired from the analysis of variance (*TABLE 4.9*) show interaction for the variables Total (p=0.0092) and Stem (p=0.0285).

Table 4.9. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil.*

Source	GLD	Total	Root	Leaf	Stem
Area	0.0038	0.0008	0.0026	0.0025	0.3093
Treat	0.0783	0.0063	0.6921	0.0227	0.0024
Area*Treat	0.9885	0.0092	0.2114	0.1212	0.0285
CV (%)	7.8	6.5	6.4	6.1	5.4

The source of this interaction stems from the different mean values for the nutrient treatments (*FIGURE 4.5*). The mean values of best entries (variable Total) for the North Eastern Cape plants were B>All>Mo>Control; and for the Jonkershoek grown plants the sequence was B>Mo>Control>All. This is similar for the variable Stem. As the source of interaction is known further analysis by area is sensible.

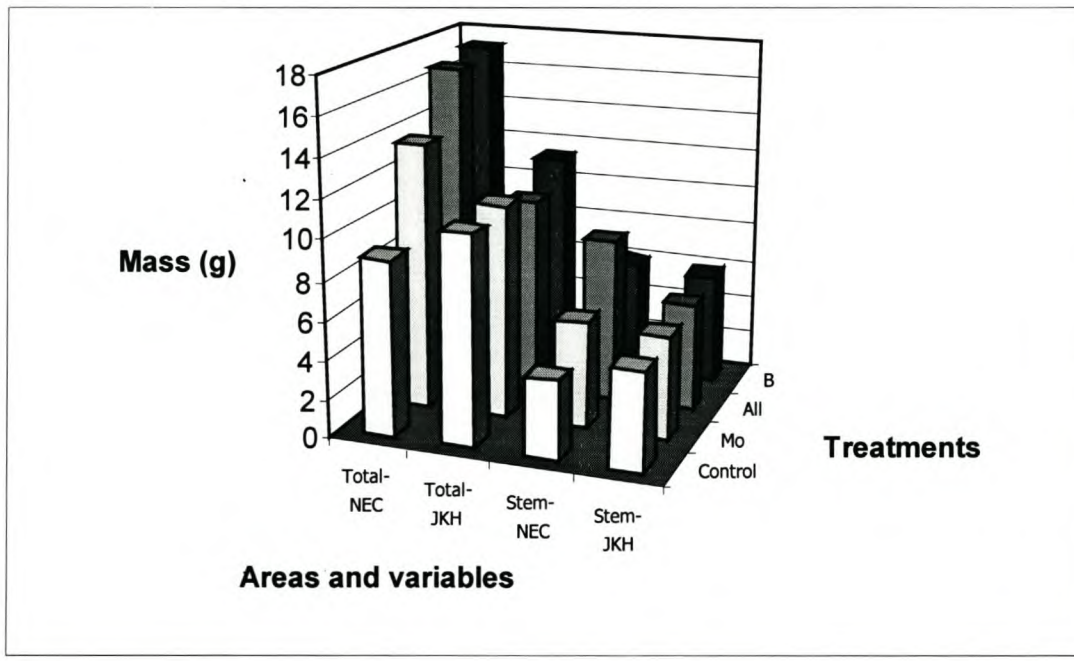


Figure 4.5 *Interaction between the biomass components of cauliflower grown on the soil from the North Eastern Cape (NEC) and Jonkershoek (JKH) areas and the various nutrient treatments for total plant mass.*

There was contradictory evidence for the effectiveness of the nutrient treatments. For variables Root and root collar diameter (RCD), the only significant difference was for the difference in soil type, whilst the variables Total, Leaf and Stem (analysis after separation of area) showed definite mean treatment differences (*TABLE 4.10*). For the variable Total and Leaf the growth of the All, B and Mo treated plants were better than the growth of the Control plants. For variable Stem the seedlings of the All treatment were the best growers with growth of the B treated plants significantly better than the growth of the Mo treated plants, but that was not significantly better than the growth of the Control plants.

Table 4.10. *Mean differences between treatments for the pot trial on North Eastern Cape soil. Different letters signify a statistical difference.*

Treatment	RCD	Total	Root	Leaf	Stem
All	7.28[a]	16.81[a]	2.87[a]	5.61[ab]	8.34[a]
B	8.02[a]	17.22[a]	3.25[a]	7.88[a]	6.09[b]
Control	7.08[a]	8.99[b]	2.17[a]	2.79[b]	4.04[c]
Mo	7.34[a]	13.72[a]	2.53[a]	5.69[ab]	5.51[bc]

The cauliflower on the Jonkershoek soil was much smaller than the cauliflower growing on the North Eastern Cape soil (*FIGURE 4.5*), but the leaf form and leaf development of the North Eastern Cape grown cauliflower was poor (*FIGURE 4.6).* This type of underdevelopment is typical of a Mo deficiency for cauliflower and is called 'whiptail'. No evidence of hollow stem disease was encountered.

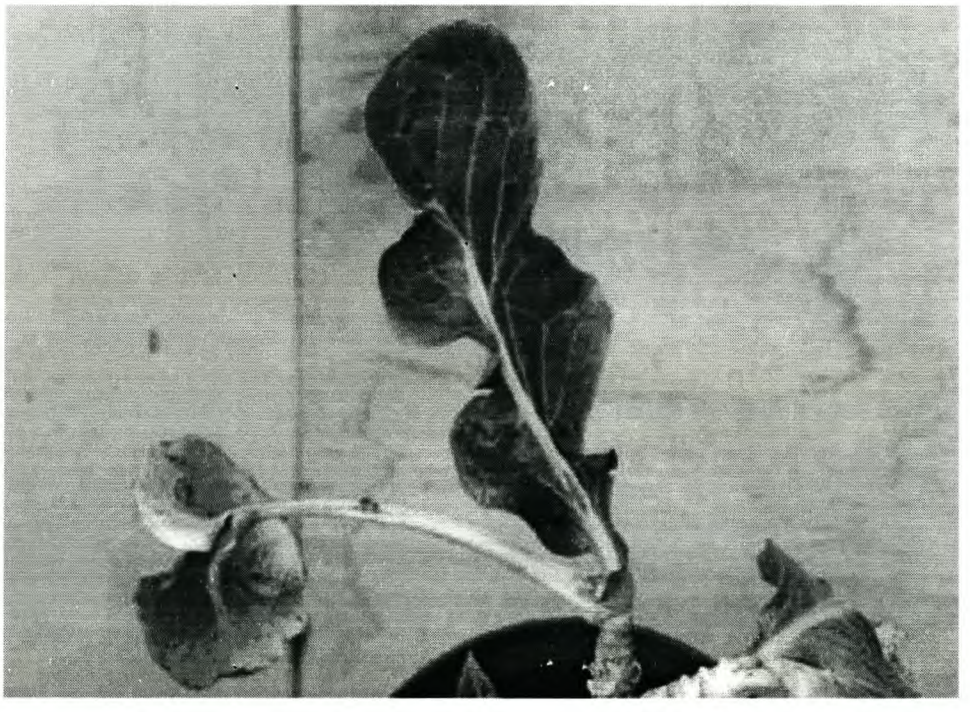


Figure 4.6 *Leaf of cauliflower grown on a problem soil from the North Eastern Cape showing typical symptoms of whiptail disease due to a Mo deficiency.*

4.1.1.6 Indicator trial: Soya

The result of the indicator trial show that there was evidence of a worst entry rather than a best entry. Although there are treatment differences for all measured variables (except for G, p=0.3206) (*TABLE 4.11*), the differences can be ascribed to the poor performance of the soya that was grown on the Mn treated soil.

Table 4.11 *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the pot trial of the North Eastern Cape soil.*

Source	Root	Total	Leaf	Stem	Podweight	H	Hbranch	G
Treat	0.0169	0.0054	0.0123	0.0333	0.0197	0.0015	0.0001	0.3206
CV (%)	5.6	6.3	5.9	6.2	6.7	4.3	4.1	6.7

The treatment means for the variables in *TABLE 4.12* show that the Mn treatment was constantly the worst performer. The Control treatment showed the best growth for most of the variables although the mean stem mass for the B treatment was the highest, the mean height of the first branch (Hbranch) for the B treatment was the highest and the mean mass of the pods was the highest for the Mo treatment (*TABLE 4.12, FIGURE 4.7*).

Table 4.12 *Treatment means for various variables. Different letters denote statistical differences. (H – plant height; Hbranch – height of first branch; G – ground line diameter).*

Treatment	Root (g)	Total (g)	Stem (g)	Pod no.	Pod mass (g)	H (mm)	Hbranch(mm)	G (mm)
B	0.89^{ab}	1.17^{ab}	0.50^{a}	1.00^{b}	0.40^{ab}	25.3^{a}	9.3^{ab}	3.21^{a}
Cu	0.72^{ab}	1.08^{ab}	0.30^{ab}	1.50^{ab}	0.47^{ab}	19.4^{b}	7.9^{ab}	2.95^{a}
Fe	0.90^{ab}	1.23^{ab}	0.31^{ab}	1.40^{ab}	0.57^{ab}	20.5^{ab}	7.4^{ab}	2.88^{a}
Control	0.97^{a}	1.42^{a}	0.40^{ab}	2.17^{a}	0.64^{ab}	25.5^{ab}	9.1^{ab}	3.23^{a}
Mn	0.54^{b}	0.80^{b}	0.34^{ab}	1.83^{ab}	0.31^{b}	18.2^{b}	2.7^{b}	2.98^{a}
Mo	0.66^{ab}	1.24^{ab}	0.24^{b}	1.67^{ab}	0.67^{a}	19.3^{b}	8.2^{ab}	2.75^{a}
Spoormix	0.88^{ab}	1.18^{ab}	0.32^{ab}	1.83^{ab}	0.52^{ab}	22.3^{ab}	8.3^{ab}	2.62^{a}
Zn	0.73^{ab}	0.91^{b}	0.29^{ab}	1.33^{ab}	0.37^{ab}	20.8^{ab}	7.3^{ab}	2.72^{a}

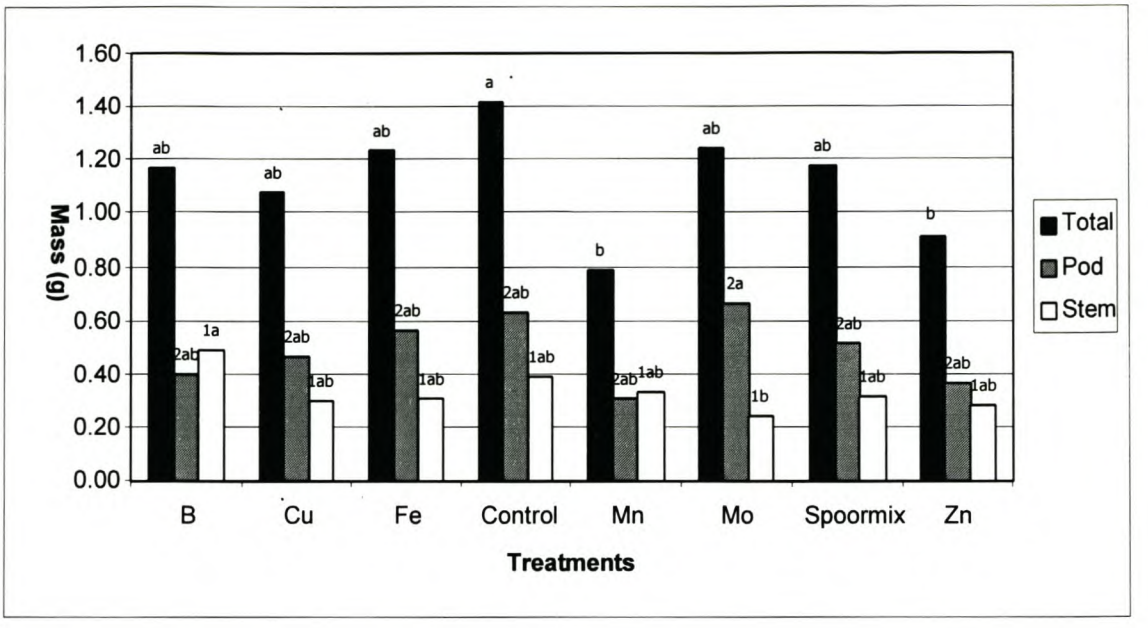


Figure 4.7 *Treatment differences for total plant mass, average pod mass and stem mass of the indicator plants grown on the pot trial from the North Eastern Cape soil. Different letters signify statistical differences.*

4.1.2 Field trials

4.1.2.1 Field plantings: Ludano

The results from the analysis of variance (*TABLE 4.13)* show that there was no interaction between the application of nutrient treatments and the type of soil cultivation. Interpretation of the main effects in *TABLE 4.13* is thus possible.

Table 4.13. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the field trial in the North Eastern Cape .*

Source	G	H	BA	BI
Cult	0.0147	0.0755	0.0092	0.0186
Fert	0.0001	0.0016	0.0001	0.0001
Cult*Fert	0.1804	0.1981	0.1732	0.1914
CV (%)	6.4	7.2	6.9	5.8

There was meaningful difference in growth due to the application of nutrient treatments ($p<0.05$ for all measured variables) (*TABLE 4.13)*. The comparison of treatment means (*TABLE 4.14)* show that the treatments containing B were consistently of the poorest growth. The Mo treated seedlings had the highest average for all the variables measured. The difference was however only significant in regards to the All and B treatments.

Table 4.14 *Treatment means for various variables measured from the field grown seedlings in the North Eastern Cape. Different letters indicate significant differences.*

Treatment	G	BA	H	BI
Mo	2.95[a]	9.00[a]	15.6[a]	152[a]
Gypsum	2.92[a]	8.89[a]	15.5[a]	151[a]
Fe	2.91[a]	8.77[a]	15.1[a]	144[a]
Control	2.75[ab]	8.21[ab]	15.5[a]	141[a]
All	2.69[bc]	7.50[bc]	13.9[ab]	112[b]
B	2.62[c]	7.18[c]	13.6[b]	109[b]

There were differences in seedling growth that could be attributed to different cultivation treatments. The p-value for H ($p=0.0755$) was the only variable that did not indicate statistically significant differences between cultivation means. The mean G, BA and BI values *(TABLE 4.15)* are the highest for treatments Scalping and Augering, and although higher than the means for Ripping, Ridging and Ploughing, it did not differ statistically significantly. There was a pronounced and significant difference between Scalping and Augering to Manual Pitting (*TABLE 4.15*).

Table 4.15 *Mean treatment values for growth measurements of the field grown seedlings in the North Eastern Cape. Different letters indicate significant differences.*

Treatment	G	H	BA	BI
Scalping	2.92[a]	15.5[a]	8.92[a]	153[a]
Augering	2.90[a]	15.3[a]	8.75[a]	145[ab]
Ripping	2.84[ab]	15.2[a]	8.40[ab]	140[ab]
Ridging	2.83[ab]	15.1[a]	8.34[ab]	135[ab]
Ploughing	2.79[ab]	14.5[a]	8.02[ab]	130[ab]
Manual pitting	2.69[b]	14.0[a]	7.59[b]	116[b]

The results of the weed score indicated that the type of cultivation influenced the growth of weeds. Of all the seedlings in the Scalping treatment, 78% received a score of 1 (least competition from weeds) and there were no seedlings that were suppressed or surrounded (score=3) by weeds. The seedlings that were planted in manually dug pits were competing on a much larger scale with the weeds and 62% of the count scored a 3. The scoring count (as a percentage) is presented in *TABLE 4.16* and it was used as a basis for Chi-square independence testing. The calculated Chi-square value of 183.97 exceeded the tabulated value of 18.31 (10 df) and therefore the null hypothesis:

H_0: Weeds are independent of cultivation treatment,

was rejected in favour of the alternative hypothesis. The presence of weeds, and thus their influence on the growth of seedlings, was determined by the type of cultivation.

Table 4.16 *Scoring count (as a percentage) of weed competition that was recorded for every seedling for a particular cultivation treatment.*

Competition score	Augering	Manual pitting	Ploughing	Ridging	Ripping	Scalping
1 (limited)	34	23	29	34	17	78
2 (intermediate)	46	15	43	48	59	22
3 (severe)	20	62	27	17	24	0

4.1.2.2. Field plantings: Sonsbeek

Severe seedling mortality was observed at the site (*TABLE 14.17*). Most of the surviving seedlings were under such drought stress that they were not expected to survive the winter. Poor survival made the collection of growth variables meaningless and mortality/survival was used as the only indicator of treatment effect.

Table 14.17 *Condition of seedlings six months after planting for various nutrient treatments.*

Condition	Mo	B	Fe	Cu	Zn	Control
Dead (%)	35	82	58	50	58	68
Alive (%)	25	8	10	3	23	15
Stressed (%)	40	10	32	47	19	18

The null hypothesis:

H_0: Seedling condition is not affected by nutrient treatment,

was tested by means of the Chi-square test of independence. The calculated value of 35.24 exceeded the tabulated Chi-square value of 18.31 (10 df) and the null hypothesis was thus rejected. Survival or mortality was dependent on one or more nutrient treatments.

The Mo treatment had the lowest mortality count (35%) which was considerably lower than the average mortality of 58%. The highest rate of mortality (83%) in the B treatment can be ascribed to a high application rate and possible toxicity. Only 28% of all the planted seedlings were expected to survive the remainder of the first season in the field.

4.1.2.3 Tree evaluation: Riverside

The mean height (Ht) of the trees (measured at trial initiation) was 4.54 m and the mean diameter at breast height (DBH) was 6.85 cm. The evaluation of the tree conditions was done in June 1999, April 2000 and October 2000. Although not in chronological order, tree conditions were evaluated in an autumn, a winter and a late spring/early summer season. Evaluation of tree condition that only occurred late in the spring of 2000 was delayed due to late seasonal rainfall. Examples of sinuous stem are shown in *APPENDIX 5.* Trees with dead leaders or multiple leaders were placed in the worst category whilst one curve in the stem of a tree demoted the particular tree to the medium category. Two or more curves in the stem resulted in placement in the poor category. A tree with one curve in the stem that was accompanied by sinous branches (more than two in whatever degree) was placed in the worst category and a tree with only sinous branches in the medium category.

During the trial period the overall tree condition worsened in that 43% of the trees that were regarded with good tree form in June 1999, was reduced to only 23% in October 2000 (*FIGURE 4.8).* In April 2000 the presence of multiple leaders (33% of all trees) resulted in the placement of 35% of the evaluated trees in the worst category. The main reason for placement in the poor tree form category in October 2000 was due to stem

sinuosity. This is an indication of problem evolution where the occurrence of multiple leaders in a forgoing season results in a crooked stem with continued growth.

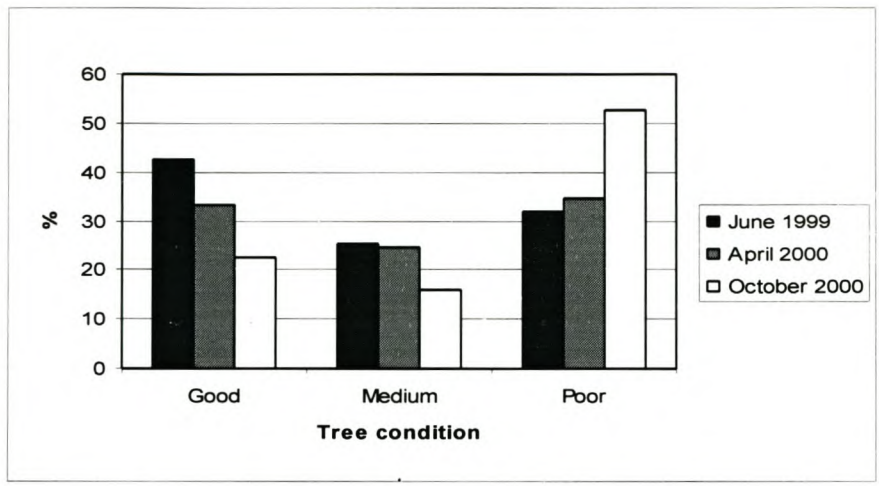


Figure 4.8 *Dynamics of tree condition over a growing season in a problem area.*

Seasonal colour changes were observed (*FIGURE 4.9*) as an overall yellowing of the foliage. The change in foliage colour (measured with Munsell colour cards) between seasons proved to be statistically significant (p=0.0004) with the greatest variation from the reference colour to be in June and April.

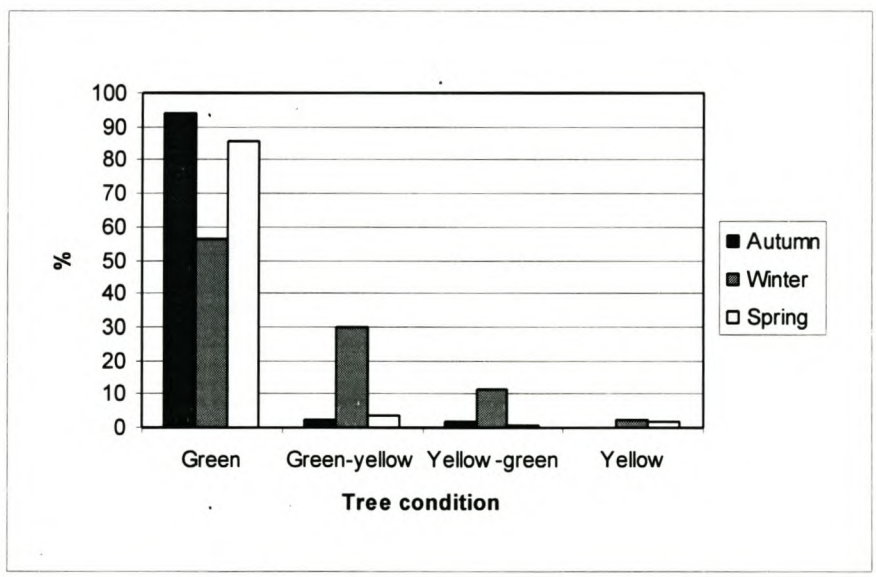


Figure 4.9 *Seasonal colour changes measured on a subjective scale*

There was no statistically significant difference in the colour of the foliage between the treated trees for the seasons of autumn (p=0.4225) and late spring (p=0.2345). For the winter period there was a statistical difference of measured colour of the foliage for the treated trees. The least variation from the reference colour was measured for the Mo and Control treatments. Comparison of the mean variation (SNK-multiple comparison) indicated least variation from the trees treated with Mo, but this was not statistically significantly different from the Control. The effect of these two treatments on foliage colour did however differ from the All, B and Fe treated trees.

The foliage analyses (*APPENDIX 1)* show that the elemental B and Mo concentrations were below the critical level of 8 p.p.m for B and 0.1 p.p.m for Mo (*APPENDIX 3)*. The foliar levels of B and Mo for the treated trees were however significantly higher than the untreated trees. Applications of these elements could be deemed successful. The foliar Fe concentrations for all the trees (including the Control treatment) were not significantly different. Absorption of Fe by the foliage thus only took place on a limited scale or not at all. Foliar nutrient concentrations for all the other nutrients were not limited or did not fall below a critical level (*APPENDIX 3)*.

4.1.2.4 Tree evaluation: Ludano

The average height (Ht) of the trees in the trial was 0.72 m and the average ground line diameter (GLD) was 53.5 mm. The trees in the trial were severely damaged by hail and thus tree condition was negatively influenced. Severe dieback of growing shoots is mostly attributed to the hail damage and the occurrence of double leaders (39%) and stem sinuosity (38%) is not necessarily the result of poor growing conditions.

Colour changes between the autumn and late spring season were indicated by means of Munsell colour cards. Less variation from the expected normal colour was observed in late spring. This was statistically different (p=0.0001) from the greater colour variation measured in autumn.

No difference between treatments with regard to foliage colour was apparent. Evaluation of colour in autumn and late spring did not indicate treatment differences.

The analyses of the foliage (APPENDIX 1) indicate that B and Mo occured below the accepted critical levels but that the Fe content was above the expected norms. Values for elemental B and Mo of the treated trees show that the B and Mo applications were successful. As in the previous trial, the application of Fe did not increase the elemental Fe foliar concentration to a level significantly higher than the control treatment. Levels of all other foliar nutrients indicated supply in sufficient amounts.

4.1.2.5 Tree evaluation: Feltham

The average Ht of the trees in the trial was 4.96 m and the average DBH was 9.55 cm. The trees were evaluated in an autumn, a winter and a late spring/ early summer season.

Colour changes of the foliage were observed and measured between the seasons. There was a significant difference ($p=0.0001$) in the variation from the normal colour of the observed foliage colour. The greatest variation was measured for the winter season that showed greater and significant variation than the late spring/ early summer measurement that was also greater and significantly different from the autumn's season colour variation. Further colour evaluation indicated a similar pattern as in *FIGURE 4.9* where the percentage of green trees in autumn (97%) and late spring/ early summer (97%) decreased in the winter season (38%).

There was insignificant variation in the classification of tree condition between the seasons. Growth in the trial block was however poor with 36% of the trees being classified as of good tree form, 23% with medium tree form and 39% with poor tree form. Multiple leaders (31%) and stem sinuosity (30%) was the major reason for classification in the medium and poor classes.

Critical Mo foliar levels were not found for *P. taeda* but in comparison it was below the 0.1 p.p.m. level that was found to be the minimum for other pine species (*APPENDIX 1).* The observed foliar B levels were also lower than the adequacy range and a B deficiency is expected. Levels of observed foliar Fe was higher than the critical level. The application of B and Mo (as in the other tree evaluation trials in the area) were more

successful than the Fe application where the foliar Fe concentrations did not differ significantly from the foliar Fe concentrations of the Control treatments. The P, Mg and Cu levels were marginal with low B and Mo levels in the Control treatment. The All treatment did improve the B and Mo levels, but the P, Mg and Cu levels did not improve. This could be the reason for the poor growth results.

4.2 Natal Midlands trials

4.2.1 Field plantings: Giants Castle

The area that was previously cultivated was completely inundated by weeds but the virgin grassland area was relatively weed free. Due to resultant unscrupulous weeding the old land part of the trial had to be aborted. The seedlings that were planted on the virgin soil were thus regarded as an independent trial.

Severe mortality (49%) occurred. A chi-square test of independence was done to determine whether this was influenced by treatment effect and the null hypothesis:

H_0: Mortality is independent of treatment application,

was rejected. The calculated chi-square value (31.47) exceeded the tabulated value of 12.59 (6 d.f.). The highest mortality was observed in the B (foliar application) treatment (91%) and the lowest mortality in the B (soil application) treatment (20%).

Although mortality may have affected the bias of the analysis, an analysis of variance was done. The results (TABLE 4.18) showed that there had been no treatment effect on the growth of the seedlings ($p>0.05$ for all variables).

Table 4.18. *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on the field grown seedlings in the Natal Midlands.*

Source	H	G	BA	BI
Treat	0.1209	0.0865	0.1306	0.1822
CV (%)	12.3	11.4	13.1	13.2

4.2.2 Tree evaluation: Harleigh

The average Ht of the trees in the trial was 4.67 m and the average DBH was 6.91 cm. There was considerable variation in tree condition throughout the trial block with 39% of the trees placed in the poor category. The occurrence of multiple leaders (36%) and stem sinuosity (21%) were the major defects.

Colour changes between seasons were not as pronounced as in other trial areas and the measured coloured variance were not of statistical proportions. No effect was observed with the application of the nutrient treatments ($p=0.6923$).

The comparison of foliar nutrient elements between healthy and poor growing trees (*APPENDIX 1*) indicated that Mo may have been deficient and B marginally low. Although the healthier looking trees also had no measurable Mo, the N content was slightly higher. The N and P nutrient levels for both healthy and poor looking trees were low enough to be of concern. All other nutrients were in the adequacy range for accepted growth.

4.3 Mpumalanga trials

4.3.1 Pot trial

The results of the analysis of variance (*TABLE 4.19*) showed that there was no three factor interaction ($p>0.05$). Interaction between the different species and the lime application was however present in all variables ($p<0.05$).

Table 4.19 *The statistical significance (p-values) for F-test results from analysis of variance on the growth measurements made on on the pot trial of the Mpumalanga soil indicating two-factor interaction.*

Source	G5	H5	Root	Above	Needle	Total
Spp	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Lime	0.5889	0.1712	0.2985	0.0735	0.1473	0.0762
Treat	0.5855	0.4091	0.1254	0.5861	0.7435	0.3777
Spp*Treat	0.7066	0.8570	0.1620	0.6408	0.6176	0.5078
Lime*Treat	0.0560	0.0933	0.1406	0.7363	0.7498	0.4835
Spp*Lime	0.0033	0.0001	0.0002	0.0001	0.0024	0.0001
Spp*Lime*Treat	0.6472	0.8300	0.9751	0.9615	0.9808	0.9820
CV (%)	5.6	6.7	5.9	6.2	6.3	6.8

The source of the interaction is clear in *FIGURE 4.10,* where the seedlings of *P. elliottii* and *P. patula* were growing better on the lime treated soil than on the unlimed soil. The opposite was true with the *P. taeda* and *E. nitens* seedlings that performed better on the unlimed soil than the lime treated soil. *P. greggii* indicated no preference either way.

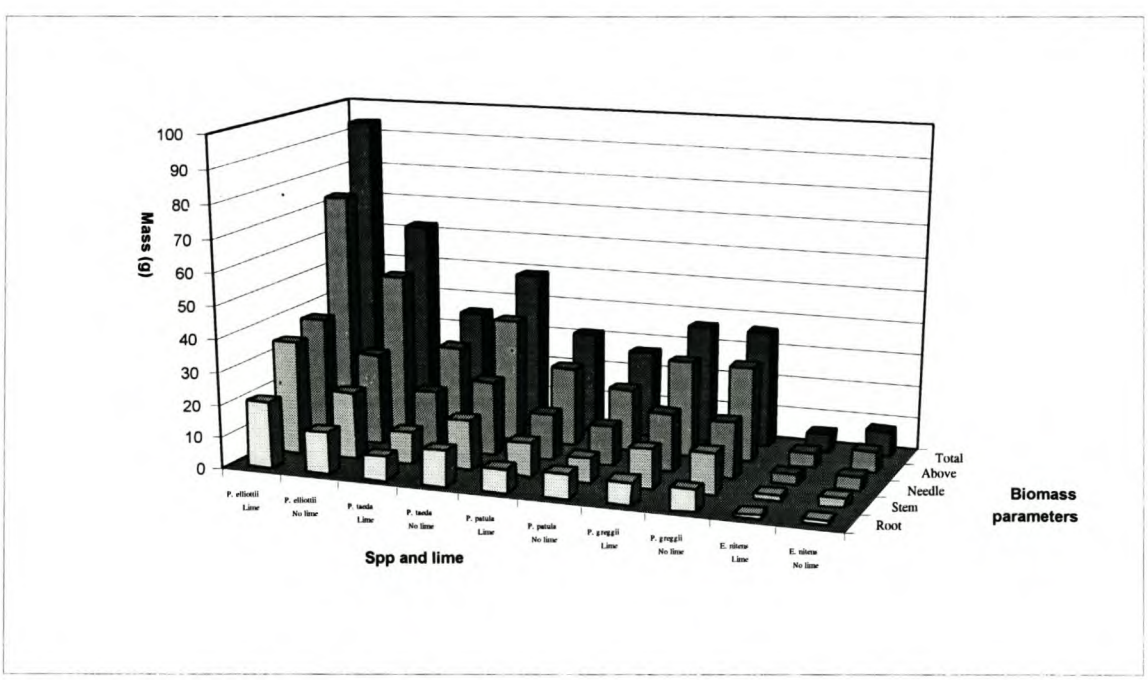


Figure 4.10 *Interaction of biomass parameters between the different species and the effect of liming for the seedlings grown on the soil from Mpumalanga.*

From *TABLE 4.19* it is possible to determine that there was no significant treatment effect. For all the measured variables $p>0.05$. The application of nutrients (B, Mo and Fe)

did not affect the growth of the seedlings to levels above the growth of the control seedlings.

Due to the interaction between the different species and the lime application it would be unwise to assume from the information presented in *TABLE 4.19* that there were significant differences between the growth of the species and to determine whether the application of lime had been effective. From *FIGURE 4.10* it can be seen that *P. elliottii* seedlings grown on the limed soil had the highest growth averages and the *E. nitens* seedlings that were grown on the limed soil were the worst performers.

Chlorosis did not manifest as was expected and all the seedlings were of the same uniform colour. There was no colour difference between the young and older foliage. There were no significant differences in colour variation from a norm colour (p=0.6547) between treatments.

4.3.2 Field trial

4.3.2.1 Tree evaluation: London

The average Ht of the trees was 5.08 m and the average DBH was 7.64 cm. The trees of this trial were chosen for investigation because of distinct foliage colour changes between the wet and dry seasons. Tree condition and growth were acceptable and most of the trees were evaluated and placed into the good tree form category (96%).

High rainfall that was recorded for the period of the trial delayed the change in foliage colour and in the winter season 94% of the trees were still evaluated as being green. In the late spring/early summer evaluation period only 43% of the trees were evaluated as being green, 24% green-yellow and 33% yellow-green. Colour changes due to treatments effect were however insignificant (p=0.2769).

The foliar analyses indicated sub-optimal levels of N, P, K, Fe and Mo (*APPENDIX 1)*. In a comparison between the healthy looking trees and the unhealthy trees the foliar analysis showed lower levels of N and Fe in the unhealthy looking trees. Most other nutrients

(except Mn) were also supplied in the lower levels of adequacy. The site earned a low fertility grading. The Mn content in the foliage bordered on toxicity.

4.3.2.2 Tree evaluation: Berlin P3

The trees in this trial measured to a Ht of 5.06 m and a DBH of 13.29 cm. The evaluated trees were of poor form and only 63% were placed in the good tree form category. A large portion of the trees had double leaders (30%) and showed signs of stem sinuosity (31%).

The high rainfall experienced in Mpumalanga also delayed colour changes in this area. In the winter season 82% of the trees were still of a green colour. Towards the end of spring this had decreased to 70%, and 22% of the trees were evaluated as having yellow-green foliage. Discolouration can be seen in *APPENDIX 5.* There was no difference in colour variation from a norm colour for the different treatments (p=0.4698).

For the particular species there was a greater variation in adaxial and abaxial colour. The outward facing side of the needles were more of a yellow hue than the shaded part of the needle.

In the comparison of the foliar nutrients (*APPENDIX 1)* between the healthier looking and unhealthy looking trees, the P and Mg were in the low class with K and Ca being marginal. The high Mn levels indicate possible toxicity. The major difference between the better growing trees and the poor trees was the lower Fe content in the poor growing trees. The adequacy range of Fe found in literature is however too large to clearly distinguish between a deficiency and levels of adequacy. Cu levels in the foliage is marginally low.

4.3.2.3 Tree evaluation: Berlin G17

The average Ht of the trees in this trial was 3.45 m and the average DBH was 4.80 cm. A large portion of the trees were placed in the poor tree form category (34%) and only 64% of the trees were evaluated with good tree form. Double leaders (32%) was the major flaw in tree condition with 15% of the trees exhibiting stem sinuosity.

The application of nutrient treatments affected the variation of foliage colour in the late spring/early summer season. Discolouration can be seen in *APPENDIX 5*. There were significant differences (p=0.0383) in foliage colour for the various nutrient treatments. The least colour variation from the desired colour was the Mo treatment. This was significantly different from the Control treatment (*TABLE 4.20*).

Table 4.20 *Differences in colour variation from a norm colour for various nutrient treatments. Different letters indicate significant differences.*

Variable	Mo	All	B	Fe	Control
Colour variation	9.71^{b}	9.92^{ab}	9.99^{ab}	10.20^{ab}	10.24^{a}

The foliar analyses (*APPENDIX 1)* support the findings of *TABLE 4.20* in that there was no Mo found in the foliar samples. A Mo deficiency was thus suspected. The Ca content of the unhealthy looking trees bordered on marginal deficiency and Mn on toxicity.

4.4 Western Cape trial

There was limited evidence of interaction between the main effects (*TABLE 4.21*). The two factor interaction that was observed for the H3 measurement was related to the poor growth of *E. nitens* on the limed soil. The sequence of height growth performance on the lime treated soil was *P. taeda>P. elliottii>P. greggii>P .patula>E. nitens* and on the unlimed soil the order was *P. taeda>P. elliottii>E. nitens>P. greggii>P. patula*. There was no interaction for the other variables.

Table 4.21 *The statistical significance (p-value) for F-test results from the analysis of variance on growth measurements made on the pot trial of the Western Cape soil.*

Source	H3	G3	Total	Above	Root	Needle	Stem
Spp	0.0001	0.4357	0.0001	0.0001	0.0001	0.0001	0.0001
Lime	0.0001	0.2740	0.0008	0.0002	0.0195	0.0007	0.0003
Treat	0.7217	0.4321	0.8129	0.8663	0.8468	0.9186	0.4566
Spp*Treat	0.3255	0.6204	0.8761	0.7942	0.8161	0.9795	0.0914
Lime*Treat	0.1836	0.4267	0.9087	0.8814	0.5173	0.8533	0.5545
Spp*Lime	0.0007	0.5115	0.7600	0.5874	0.9612	0.5981	0.3999
Spp*Lime*Treat	0.8540	0.5206	0.6107	0.7520	0.4682	0.8417	0.4938
CV (%)	12.1	10.9	11.1	9.8	9.6	10.3	9.9

The G3 variable indicated no main effects ($p>0.05$) but this was not the case for all the other variables ($p<0.05$). There was pronounced difference in growth between the different species ($p<0.05$) and the addition of lime proved not to be beneficial ($p<0.05$). No nutrient treatment effect was observed ($p>0.05$).

The *P. elliottii* seedlings were constantly the best performers in terms of biomass production (*TABLE 4.22)*. Although growth did not differ significantly from that of the *E. nitens* seedlings, it was better than the growth of *P. greggii* and *P. taeda* that in turn was significantly better than the growth of the *P. patula* seedlings.

Table 4.22 *Differences between species for certain growth variables for the seedlings grown in pots on a soil from the Western Cape. Different letters indicate significant differences.*

Species	Total	Roots	Above
P. elliottii	1.42^{a}	0.47^{a}	0.95^{a}
E. nitens	1.24^{a}	0.43^{a}	0.80^{b}
P. greggii	0.88^{b}	0.32^{b}	0.56^{c}
P. taeda	0.69^{bc}	0.33^{b}	0.35^{d}
P. patula	0.59^{c}	0.11^{c}	0.48^{cd}

5. Discussion

In this chapter the trials are discussed by region of investigation. The general sequence of trials in the **Chapter 4** is followed.

The trials conducted in the North Eastern Cape and pot trials on soil from that area indicate conflicting results with regards to the various nutrient treatments from the different trial sites. Differences between species and the site fertility of the trials are of vital importance when conclusions are drawn from these trials. Although the rainfall over the general area of the trial sites and soil collection sites are the same, the variations in soil fertility and microclimate are the most influential growth factors. This was apparent

with seedlings grown in the pot trials where soil has been collected from two different sites (Ludano and Sonsbeek).

The seedlings grown in the Sonsbeek soil showed greater reaction to the application of nutrients than the seedlings of the Ludano trials. This may be an indication of inherent fertility of certain areas or remnants of fertilised old agricultural lands. The Sonsbeek soil is of virgin grasslands and thus a difference between the ex-agricultural lands and the virgin grasslands are suspected. This is consistent with findings in the area by Noble (1990), Noble and Schuman (1993), Schuman and Noble (1993) and Schuman *et al.* (1994).

In the liming trial of the North Eastern Cape the lime-induced chlorosis was the dominant effect. There was however a noticeable difference between the various species and the various nutrient treatment applications. To understand the interaction between the addition of lime, the species and the application of nutrients, it was necessary to partition the trial by lime and by species. Of the various species, *P. greggii* indicated the greatest reaction to nutrient application. The All and the B treatments increased the growth of *P. greggii* seedlings to levels significantly higher than the seedlings of the other treatments.

The various species indicated that the growth reaction to large quantities of lime was negative and any possible reaction to nutrient application was obscured. On the unlimed soil the application of B had a positive and significant effect on the growth of the seedlings. A probable Mo-toxicity was cause for the seedlings of the Mo treatment performing on average poorer than the Control treatment seedlings and significantly poorer than the B treated seedlings. The positive reaction to B application was a confirmation of field observations of tip dieback and sinuous growth patterns that are symptomatic of a B deficiency.

The seedling growth rates indicated that *P. elliottii* was the fastest grower. This was found to be the case in the liming trials of all the other regions. In most cases this species was a better performer than *E. nitens* and *P. taeda*, and significantly better than *P. greggii* and *P. patula*. In the plantations of the North Eastern Cape field observations and growth measurements (Zwolinski, *pers. comm.*, 1998) confirm that *P. elliottii* is mostly planted to the harsher and problem growing areas.

The nutrient trial conducted on a similar soil than the liming trial, indicated no growth difference between seedlings treated with a range of nutrients. Initial growth differences between the treatments decreased with time. Suspected B toxicity was however expected for the B treated seedlings due to high levels of B application for the particular trial. The growth of the B treated seedlings was negatively affected. Similar results were encountered with the soya indicator trial where no preference to any nutrient was shown in the growth performance. The nutrients were however applied at the same amounts and toxicity of B was again suspected.

The growth reaction to singular elemental B, Fe, Mo and P nutrient applications in the Sonsbeek nutrient trial was a good indication that some of these nutrients were deficient at the specific trial site. The seedlings treated with these nutrients performed as well as seedlings treated with a complete fertiliser application of N, P and K (2:3:2 (22)) and performed distinctly better than the control seedlings. Favourable growth reactions to all of these nutrients are a definite indication that multiple deficiencies exist. Trials that test the interaction between them are needed to confirm their co-ordinated function.

The pasteurisation trial indicated that there is a definite benefit to mycorrhizal inoculation and that P fertility is a major concern on the virgin soils. The P deficiency of the red, acid and apedal soils is part of the multiple deficiencies that occur in the region and was very symptomatically displayed on the pine seedlings of the trial. The deficiency was confirmed by use of the dichotomous key that Lyle (1969) developed for identification of nutrient deficiencies in greenhouse grown pines. There was no preference to N source. This has been found by various authors (Nakos, 1980; Mead, 1984; Noble and Schuman, 1993; Schuman *et al.*, 1994; Jarvel, 1996) to be the case with many pine species where N feeding is rather dependent on site factors like high $CaCO_3$ content and high organic matter content in the soil. Trees should prefer the uptake of NH_4-N because it is more efficient in the plant and it is not subjected to as much leaching and denitrification as NO_3-N. Nitrate nitrogen in the plant has to be reduced to the NH_4-N by a Mo-containing enzyme before it can be utilized (Uabert and Pinta, 1977; Kabata-Pendias and Pendias, 1985). Plants that take up the NO_3-N source is more prone to Mo deficiencies but due to the greater need for P, a possible Mo deficiency was obscured. In similar pot trials that were done with *P. patula* grown on soil from the same location, reaction to Mo

application was observed after the P deficiency was satisfied by the addition of a N, P and K fertiliser to young plants (Buchler, 1997).

Good results were attained from the cauliflower indicator trials. The soil in this trial was the same as the soil from the Sonsbeek nutrient trial where severe nutrient deficiencies were observed and significant reaction to Mo, B, and NPK was found. The visual deficiency symptoms of the cauliflower grown on the North Eastern Cape soil are a classic feature of Mo deficiency (whiptail disease) (Hewitt, 1966; Marschner, 1997). The application of B and Mo did increase the biomass of the treated cauliflower plants to a level that is significantly higher than that of the Control cauliflower, but other deficiencies (possibly P deficiency) are also expected.

The establishment of field trials in the Ludano trial site indicated the effect of weeds on seedling growth and survival. The various methods of cultivation had a large influence on the growth of weeds and this in turn significantly affected the growth of the seedlings. The seedlings grew better where the seed source of the weeds was removed (scalping and ridging). High mortality was observed where the seedlings were planted in manually dug pits with limited or no effect on weed growth. There was no increased growth reaction to the application of any nutrient treatment. Toxicity of B was however noted and this negatively affected the growth of the seedlings treated with B. It is necessary to repeat similar trials to determine the effect of B on seedling growth and to determine optimum amounts of B fertiliser application. Results of this trial are not conclusive to the effectiveness of B application. All the trees that were treated as bad however showed a deficeincy in B of Mo, or both and toxic levels of Mn. A deficiency of Mg and Cu also occurred.

Field plantings at Sonsbeek resulted in high mortality. The application of B however resulted in mortality above levels caused by the environment and B toxicity was again suspected. Severe mortality in this compartment could otherwise be ascribed to extreme environmental conditions. In a study by Fyfield *et al.* (1998), the conditions at Sonsbeek were monitored and results indicate an average of forty nights per year where the temperature drops to between 0 and –5 ^{0}C and two to nine nights per year to below –5 ^{0}C. This compares unfavourably to sites in other forestry parts where there are twelve or less nights where the temperature drops to between 0 and –5 ^{0}C. The hydromorphic status of

the soil indicates severe moisture stress and that successful afforestation of the area can only be attained by planting early in the growing season during very wet years. An efficient root system must be established before the onset of winter and only correct soil preparation and the addition of nutrients can achieve this.

The evaluation of trees in established compartments indicated a high portion of trees with poor growth and bad tree form. Bad tree form develops from the occurrence of growth problems over a number of years. Tip dieback of leader shoots at the end of the dry season leads to the formation of multiple leaders. With the onset of the growing season one leader gains apical dominance and a bend in the stem is formed. During the dry season of the following year this leader dies and multiple leaders are again formed. Stem sinuosity then increases as one of the shoots again becomes the leader. The repeated dieback results in multiple leaders with lack in apical dominance and the trees have a bushy appearance. These symptoms and the production of resin droplets are consistent with B deficiency symptoms diagnosed by various authors (Stone and Will, 1965; Snowdon, 1980; Lambert *et al.*, 1997).

There was a significant difference in the seasonal colour variation of the foliage measured by means of subjective analyses and Munsell colour cards. The yellowing of the foliage colour is a probable indication of growth stress during the cold and dry season. A deficiency in nutrients will increase the severity and length of yellowing and thus positive reaction to nutrient application was measured as degree of yellowing during the dry season and the rate of recovery after the first rains. Foliage colour was thus measured after the first rains, but change in foliage colour between all treatments was too rapid for statistical differences to be measured. The application of nutrients will not prevent total discolouring of foliage during the dry season but the degree of yellowing would be limited. In this study there was however only one trial site (Berlin M32) where colour differences between treated and control trees were significant. Monitoring of the rate of continual colour change was not feasible in this study and assessment had to be confined to singular visits and was dependent on reports of rainfall. In all the regions where tree condition was measured, the general trend of yellowing during the winter/dry season was observed. Foliage discolouration was not directly associated with poor stem form but was taken as an indication of nutrient stress.

The field trials in the Natal Midlands confirmed the problem with weeds. Most of the planted seedlings on the old agricultural soils were succumbed by weed competition. This seemed to be the major factor in determining seedling mortality in the old lands. In the trial on the virgin grasslands, the application of nutrients had no significant effect on the growth of the seedlings. The foliar and soil applications of B were however too high and severe foliar scorch and seedling mortality occurred on the B treated seedlings.

Nutrient studies in the Natal Midlands have indicated the need for nutrient applications to address specific nutrient deficiencies. Growth reaction of young *P. patula* stands to P, K and Mg fertiliser application was found by Du Toit and Job (1999) in nutrient trials at Harleigh. Studies have also indicated that B deficiencies of avocado trees in the Natal Midlands are widespread (Bard, 1997) and occur on the highly weathered, leached, well-drained oxisols in the mist belt region. Boron deficiencies have been found to be a severe problem in South African avocado orchards and most of the deficiency symptoms have been unrecognized until recently. Multiple deficiencies are thus encountered in this area and further studies are needed that could provide answers to specific nutrients to be applied to forest crops and to determine the rates of application.

In the liming trial on the soil from Mpumalanga the interaction between the different species and the effect of lime addition was of interest. Two of the tested species (*P. elliottii* and *P. patula)* preferred the addition of lime while *P. taeda* and *E. nitens* grew better on the unlimed soil. There was no significant effect to the addition of the nutrient treatments. Poor growth in the area can be attributed to Mn toxicity, exhibited as either a K deficiency (Schutz, 1989; Viljoen, 1991), Fe deficiency (Ellis, 1999) or a Mg deficiency (Marschner, 1997). Soil aeration possibly resulted in oxidization of Mn in the soil and therefore toxicity in the pot trials was not as pronounced as in the field trials.

The high rainfall before evaluation of treatment effects in the established stands alleviated possible nutrient stress and responses to application of nutrient treatments in areas where specifically Mn toxicity is expected, was not observed. In contrast to foliar application and subsequent analyses of trials in the North Eastern Cape, the application of Fe to pine foliage in Mpumalanga was also regarded as ineffective. Methods of improving adsorption of Fe should be investigated to clarify actual Fe requirements.

The seedlings grown on the soil from the Western Cape soil indicated no treatment effects. The soil analysis indicated that there is little or no Zn in the soil and a Zn deficiency was suspected. There was a similar reaction to the application of lime as was found in the liming trial on the Mpumalanga soil. The best performing species was again *P. elliottii,* with *E. nitens* growing the worst on the limed soil.

The negative reaction to some of the nutrient treatments has resulted in revision of some application rates. The B toxicity observed on many of the field plantings is an indication that the application rate was too high. A rate of 1 g/tree of Boronate (16.5% B) is recommended. The amount of active ingredient per tree must not be more than 0.25 g. The foliar application also resulted in some scorch and the rate of application should be decreased to 2.0 g/l. The positive growth of the Mo-soaked seeds in the Sonsbeek nutrient trial is an indication that the rate of 0.17 g/l was adequate and is recommended. There is however concern about the adsorption of Fe (applied as Fe-EDTA) by the foliage of pine trees. Research is needed to find proper wetting agents and to establish optimum application rates. No signs of toxicity were observed for any other treatments, but the rates of application should be regarded as a minimum rather than an optimum. Further research is needed to confirm levels of toxicity.

6. Conclusions

Poor growth and growth abnormalities were observed in many different location in some of the plantation forestry regions of South Africa. It would be impossible for a study of this nature to investigate all nutrient deficiencies throughout the plantation forests of South Africa. An attempt has however been made to link nutrient imbalance to growth aberrations and some methods used in the study proved to be useful in this regard. Due to the magnitude of variables that affect tree growth, a high intensity study over a period of many years in each particular region is necessary to determine exact problems and how to overcome them. This study was limited to specific nutrients that were thought to be major contributors to poor growth and it is possible that other influential nutrients were overlooked.

This study highlighted the complexity of nutritional studies. Many interacting factors influence growth and nutrients are but one in a network of constraints that need to be

understood. Field observations were often complicated by multiple deficiency problems and nutrient imbalances that cause both toxicity and deficiency in different nutrients.

Control over environmental conditions in the pot trials simplified the acquisition and analyses of data. This was in contrast to the field trials where unfavourable and unseasonal weather conditions influenced and delayed the outcome of many trials. Higher than average rainfall in Mpumalanga, the North Eastern Cape and the Natal Midlands was recorded for the period of the trials, which alleviated growth stress to such an extent that seasonal foliage colour changes were minimal compared to other years.

The use of bio-assays did however expose the inherent problem of pot trials where growing conditions in a nursery are different to those in the field. The collection of soil disrupted the natural state of the growing medium and after increased oxidisation the potted soil was very different from the soil in its natural state. This was particularly true where the effect of Mn toxicity was diluted on the Mpumalanga soil.

The use of soil from the B-horizon for most of the pot trials was justified in that most growth problems were observed in areas where the topsoil was removed. In cultivation treatments *eg.* scalping, the topsoil was removed to minimise the effect of weed competion and in certain areas loss occurred through slash burning and subsequent erosion. In old farmlands there was little distinction between surface and subsoil horizons as years of cultivation had led to soil assimilation of the soil layers.

The system of tree evaluation was mostly an indication of current tree condition. A decline in tree form in some areas was however noted where evaluation spanned two years. It can be reasoned that this decline in tree condition was due to growth stress and growth aberrations of previous years that were only manifested in the seasons of evaluation. The application of nutrients could not improve the conditions of the current crop as malformations of stem sinuosity and forked trees were already present. The aim of nutrient application was not to improve tree form but to observe possible positive growth reactions like colour changes.

Differences in foliar colour between various nutrient treatments that were measured in the North Eastern Cape are a positive indication to evaluate the effectiveness of nutrient

applications. The timing and magnitude of colour measurement should however be linked to seasonal variation.

The use of soil analyses and foliar analyses proved to be useful in the identification of nutrient imbalances observed in some of the growing areas. This was however only evident in cases where distinct deficiencies and or toxicities were observed. Due to lack of a suitable database and other nutritional information it was impossible to confirm these imbalances by use of the DRIS system. The cost of foliar analyses made the use of vector analysis in the pot trials impractical and differences between the treatments could only be observed as growth differences.

In the North Eastern Cape and the Natal Midlands poor growth can not only be attributed to nutrient imbalances. The field trials indicated that the negative effect of weeds largely contributed to the poor growth and mortality of trees and seedlings. Whether the effects of the weeds were due to direct competition or to residual chemicals in the soil, has not been addressed in this study.

In the pot trials there were a pronounced differences in the growth rates of the species. For most of the pot trials the *P. elliottii, P. taeda* and *E. nitens* seedlings were better growers than *P. greggii* and *P. patula* seedlings. In the Mpumalanga pot trial the *P. elliottii* and *P. patula* seedlings seemed to prefer the addition of lime to the growing medium. This was in contrast to the *P. taeda* and *E. nitens* seedlings that performed better in the unlimed soil. *P. greggii* seedling growth was not affected by the addition of lime.

The results of cauliflower as an indicator species proved to be useful in the visual identification of a Mo deficiency. Suspected compound nutrient deficiencies however complicate a conclusion being drawn to a single nutrient deficiency. The addition of Mo as a remedial treatment would only pronounce subsequent deficiencies of P, B or Ca in the North Eastern Cape sites.

The necrosis and mortality caused by the B treatments in many of the trials was disappointing. This however confirmed the narrow margin between levels of sufficiency and toxicity. Fertilisers that contain B should not be applied at rates above those found to

be sufficient in this study. Foliar Fe application of mature trees should be carefully considered. The study indicated that absorption is minimal when applied with a wetting agent, even at rates higher than specified by the suppliers. Further studies are needed to determine rates, methods and sources of nutrients to be applied to trees.

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APPENDIX 1. Measured foliar nutrient content of the various trials.

Trial (as in text)	Area	Species	Notes	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B	Mo
				(%)					mg/kg						
4.2.2	Harleigh	P. patula	Good	1.17	0.10	0.53	0.65	0.20	349	514	209	9	58	16	Undetected
4.2.2	Harleigh	P. patula	Bad	1.29	0.11	0.54	0.33	0.21	338	498	180	7	27	11	Undetected
4.3.2.1	London	P. patula	Good	0.86	0.07	0.37	0.58	0.15	234	2373	228	5	17	9	0.07
4.3.2.1	London	P. patula	Bad	0.56	0.07	0.33	0.43	0.27	212	2309	97	4	19	11	0.09
4.3.2.3	Berlin	P. patula	Bad	1.13	0.09	0.30	0.14	0.10	182	857	87	5	13	11	Undetected
4.3.2.3	Berlin	P. patula	Good	1.38	0.09	0.41	0.23	0.14	222	775	79	6	53	10	Undetected
4.3.2.2	Berlin	P. elliottii	Good	1.70	0.09	0.25	0.43	0.13	343	5526	245	6	71	14	0.23
4.3.2.2	Berlin	P. elliottii	Bad	1.66	0.08	0.19	0.18	0.08	806	3185	146	8	39	11	0.15
4.3.2.2	Berlin	P. elliottii	Good	1.37	0.09	0.49	0.36	0.08	300	3676	127	4	22	19	4.18
4.3.2.2	Berlin	P. elliottii	Bad	1.62	0.10	0.31	0.41	0.05	111	3412	76	4	44	16	2.40
4.3.2.3	Berlin	P. patula	Bad	1.43	0.09	0.12	0.51	0.11	225	8072	169	5	26	46	Undetected
4.3.2.3	Berlin	P. patula	Good	1.55	0.10	0.37	0.18	0.07	127	3396	88	5	21	9	2.35
4.1.2.3	Ludano	P. patula	Mo-treatment	1.67	0.11	0.67	0.59	0.19	198	741	170	4	17	6	0.579
4.1.2.3	Ludano	P. patula	B-treatment	1.58	0.1	0.64	0.58	0.15	227	758	179	5	16	80	0.005
4.1.2.3	Ludano	P. patula	Fe-treatment	1.73	0.11	0.74	0.55	0.15	191	704	165	4	17	11	0.026
4.1.2.3	Ludano	P. patula	All treatment	1.64	0.1	0.65	0.78	0.2	199	1123	145	3	15	69	0.921
4.1.2.3	Ludano	P. patula	Control	1.63	0.1	0.75	0.51	0.13	199	605	182	3	14	10	0.022
4.1.2.3	Ludano	P. patula	Mo-treatment	1.66	0.11	0.67	0.47	0.12	180	895	148	3	19	8	1.02
4.1.2.3	Ludano	P. patula	B-treatment	1.55	0.1	0.68	0.47	0.15	216	686	140	3	16	35	0.047
4.1.2.3	Ludano	P. patula	Fe-treatment	1.95	0.12	0.68	0.49	0.11	242	1142	164	4	19	6	0.017
4.1.2.3	Ludano	P. patula	All treatment	1.53	0.1	0.59	0.41	0.13	209	983	134	3	18	91	0.541
4.1.2.3	Ludano	P. patula	Control	1.54	0.11	0.61	0.38	0.11	196	736	130	3	15	7	0.009
4.1.2.4	Riverside	P. patula	Mo-treatment	1.65	0.12	0.71	1.2	0.17	185	1192	112	3	36	15	0.009
4.1.2.4	Riverside	P. patula	B-treatment	1.74	0.15	0.66	1.42	0.24	209	1021	119	4	44	45	0.005
4.1.2.4	Riverside	P. patula	Fe-treatment	1.91	0.16	0.7	0.74	0.22	165	1139	200	4	41	16	0.005
4.1.2.4	Riverside	P. patula	All treatment	1.67	0.15	0.78	0.9	0.23	200	1035	113	4	40	41	0.923
4.1.2.4	Riverside	P. patula	Control	1.59	0.13	0.69	0.93	0.17	191	511	105	4	44	9	0.11
4.1.2.4	Riverside	P. patula	Mo-treatment	1.68	0.14	0.88	0.63	0.19	218	821	108	4	39	10	0.127
4.1.2.4	Riverside	P. patula	B-treatment	1.59	0.13	0.71	0.63	0.18	230	568	117	4	33	39	0.005
4.1.2.4	Riverside	P. patula	Fe-treatment	1.71	0.15	0.65	0.84	0.23	197	1259	137	4	40	13	0.002
4.1.2.4	Riverside	P. patula	All treatment	1.75	0.12	0.72	0.85	0.15	193	716	108	4	33	21	0.185
4.1.2.4	Riverside	P. patula	Control	1.52	0.13	0.54	0.59	0.18	214	933	148	3	26	8	0.014

Trial (as in text)	Area	Species	Notes	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B	Mo
				(%)					mg/kg						
4.1.2.5	Feltham	P. taeda	Mo-treatment	1.56	0.11	0.64	0.58	0.13	179	1291	170	4	22	5	0.014
4.1.2.5	Feltham	P. taeda	B-treatment	1.66	0.11	0.61	0.45	0.12	199	1235	144	4	28	56	0.09
4.1.2.5	Feltham	P. taeda	Fe-treatment	1.72	0.1	0.59	0.47	0.13	177	969	188	4	20	8	0.006
4.1.2.5	Feltham	P. taeda	All treatment	1.55	0.11	0.64	0.43	0.12	179	510	193	4	12	24	0.208
4.1.2.5	Feltham	P. taeda	Control	1.1	0.09	0.6	0.56	0.14	202	1616	265	4	26	11	0.566
4.1.2.5	Feltham	P. taeda	Mo-treatment	1.61	0.11	0.73	0.52	0.13	187	1302	120	3	17	6	0.566
4.1.2.5	Feltham	P. taeda	B-treatment	1.46	0.1	0.53	0.52	0.12	177	1237	138	3	23	24	0.026
4.1.2.5.	Feltham	P. taeda	Fe-treatment	1.59	0.1	0.7	0.55	0.15	176	1771	108	4	28	7	0.09
4.1.2.5	Feltham	P. taeda	All treatment	1.37	0.1	0.56	0.39	0.12	237	896	112	3	19	25	0.512
4.1.2.5	Feltham	P. taeda	Control	1.51	0.1	0.45	0.34	0.1	167	763	102	4	18	7	0.026

APPENDIX 2. Soil analyses for the different trial areas and pot trials

Trial	Area	pH (KCl)	Resistance (ohm)	H cmol /kg	P	K	Exchangeable cations (cmol(+)kg)					Cu	Zn	Mn	B	S
					mg/kg		Na	K	Ca	Mg	S-value	mg/kg				
4.2	Harleigh	4.8	5920	3.63	2	40	0.08	0.10	2.58	0.73	7.12	0.90	1.3	6.2	0.80	28.47
4.2.1	Giants Castle	4.6	3430	4.15	13	144	0.08	0.37	1.81	1.14	7.55	0.70	1.0	2.1	0.90	42.47
4.1.2.2	Sonsbeek	4.1	9610	1.91	2	47	0.03	0.12	0.45	0.29	2.80	1.00	0.1	26.1	0.10	-
4.4	Jonkershoek	4.5	20000	2.48	3	24	0.05	0.06	0.16	0.03	2.78	0.10	0.0	2.6	0.10	-
4.3.2.1	London	4.7	6220	3.63	2	28	0.04	0.07	1.36	0.54	5.64	3.00	0.3	75.7	0.70	-
4.3.2.3	Berlin M32	5.0	2600	0.00	0	387	0.27	0.99	0.47	3.26	4.99	13.86	9.4	52.7	0.11	-
4.3.2.2	Berlin P3	4.7	3650	1.23	1	67	0.28	0.73	0.36	2.75	5.35	5.26	3.3	35.1	0.11	-
4.1.2.5	Feltham	4.2	9430	1.77	1	51	0.25	0.13	0.65	0.35	3.15	1.48	0.3	6.6	0.11	-
4.1.1.2	Ludano BO4	4.2	8750	1.84	5	9	0.07	0.26	1.53	1.05	4.75	0.65	1.2	3.2	0.85	-
4.1.2.3	Ludano BO1	4.1	7630	1.79	2	3	0.08	0.14	0.56	0.53	3.10	0.85	0.7	10.2	0.10	-
4.1.2.4	Riverside	5.3	3860	0.00	1	164	0.29	0.42	2.79	1.33	4.83	1.69	0.4	4.7	0.09	

APPENDIX 3. Foliar element concentrations for some plantation forest species (N, P, K, Ca, Mg, S - %; Cu, Zn, B, Fe, Mn, Mo – $mgkg^{-1}$).

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. caribaea	N	Seedling (12 months)				1.39-1.97					Hart *et al.* (1980)
		Young plants (2 – 4 years)			0.8-1.0	1.0-1.1					Cameron *et al.* (1982)
		Young stands	0.62			1.07					Van den Burg (1985)
		Plantations		< 0.80	0.9	1.29					Reuter and Robertson (1993)
		Adult stands				0.87-0.88					Stewart and Kellman (1982)
	P	Seedling (12 months)			< 0.07	0.07					Hart *et al.* (1980)
		Young plants (2 – 4 years)			0.05-0.08	0.09-0.14					Cameron *et al.* (1982)
		Young stands	0.05	0.05-0.06	0.06-0.08	0.08-0.10	0.10-0.11				Van den Burg (1985)
		Plantations		0.065		0.17					Reuter and Robertson (1993)
		Young stands	0.02			0.08					Van den Burg (1985)
		Adult stands			0.05-0.06						Stewart and Kellman (1982)
	K	Seedling (12 months)				0.72-1.49					Hart *et al.* (1980)
		Young plants (2 – 4 years)			0.26-0.48	0.52-0.67					Cameron *et al.* (1982)
		Young stands	0.23			0.43-1.35					Van den Burg (1985)
		Young stands				0.40-0.50					Van den Burg (1985)
		Plantations		< 0.30							Reuter and Robertson (1993)
		Adult stands				0.17-0.24					Stewart and Kellman (1982)
		Adult stands				0.35-0.49					Stewart and Kellman (1982)
	Ca	Seedling (12 months)				0.39-1.12					Hart *et al.* (1980)
		Young plants (2 – 4 years)				0.10-0.30					Cameron *et al.* (1982)
		Plantations		< 0.11							Reuter and Robertson (1993)
	Mg	Seedlings (12 months)				0.12-0.31					Hart *et al.* (1980)
		Young plants (2 – 4 years)				0.07-0.19					Cameron *et al.* (1982)
		Young stands			0.04	0.05-0.13					Van den Burg (1985)
		Plantations		< 0.80							Reuter and Robertson (1993)
		Adult stands				0.09-0.10					Stewart and Kellman (1982)
	S	Seedlings (12 months)				0.12-0.32					Hart *et al.* (1980)
		Young plants (2 – 4 years)				0.06-0.08					Cameron *et al.* (1982)
	S (SO_4-S)	Plantations			0.03	0.089					Reuter and Robertson (1993)
	Cu	Young plants (2 – 4 years)			1.6-2.2	2.4-3.5					Cameron *et al.* (1982)
		Plantations		< 2.0		7.3					Reuter and Robertson (1993)
		Young stands				2.7-5.4					Van den Burg (1985)
	Zn	Seedlings (12 months)				22-57					Hart *et al.* (1980)
		Young plants (2 – 4 years)			4.8-7.5	10.2-13 4					Cameron *et al.* (1982)
	B	Young stands	4-9	< 9	9	10-21					Van den Burg (1985)
		Plantations		4-5	< 10	33					Reuter and Robertson (1993)
	Fe	Seedlings (12 months)				296-1003					Hart *et al.* (1980)
		Young plants (2 – 4 years)				24-98					Cameron *et al.* (1982)
		Young stands				56-141					Van den Burg (1985)
	Mn	Seedlings (12 months)				182-200					Hart *et al.* (1980)
		Young plants (2 – 4 years)			12-40	72-148					Cameron *et al.* (1982)
		Young stands				219-740					Van den Burg (1985)
P. elliottii	N	Seedlings in sand culture			0.94-1.5	1.5-2.0	2.0-2.5	2.5-4.2			McGee (1969)
		Seedlings in pot trial				1.27					McKee (1978)
		Young plant (2-4 yrs)				1.27					Bengston (1976)
		Young plants in field			1.04-1.17	1.18-1.42					Bengston and Smart (1981)
		Nursery crop				1.60					Donald and Young (1982)
		Young plantations				1.02-1.11					Waring (1980)
		Plantations				0.09-1.10					Anon. (1997)
		Plantations			0.84						Van den Burg (1985)
		Young stands			0.95-1.13	1.29-1.40					Shoulders and Tiarks (1980)
		Young stands		1.00	1.00-1.20	> 1.20					Van den Burg (1985)
		Young stands				1.2-1.5					Van den Burg (1985)
		Young stands		1.0-1.1	1.1-1.4	1.3-2.2		> 2.0			Van den Burg (1985)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. elliottii	P	Seedlings in sand culture			0.03-0.08	0.11-0.43					McGee (1969)
		Seedlings in pot trial				0.15					McKee (1978)
		Seedlings in pot trial			< 0.07						Terman and Bengtson (1973)
		Seedlings in pot trial			< 0.07						Van den Burg (1985)
		Young plants (2-4yrs)				0.14					Bengtson (1978)
		Young plants in pot (2yrs)			0.04	0.06-0.08					Jahromi *et al.* (1976)
		Young plants in pot (3-4yrs)			< 0.10						Pritchett and Llewellyn (1966)
		Nursery crop				0.26					Donald and Young (1982)
		Young plantations				0.13-0.16					Waring (1980)
		Young plantations	0.05			0.06					White and Mead (1971)
		Plantations			0.07-0.08						Reuter and Robertson (1993)
		Plantations				0.08-0.10					Anon. (1997)
		Plantations			0.07						Van den Burg (1985)
		Young stands			0.08-0.10						Schutz (1976)
		Young stands			0.08	0.10-0.15					Shoulders and Tiarks (1980)
		Young stands			0.04-0.07	0.07-0.09	> 0.09				Terman and Bengtson (1973)
					< 0.08	> 0.08					Bevege and Richards (1972)
				0.09-0.10	0.06-0.13	0.10-0.30					Van den Burg (1985)
		Stands			<0.08-0.09						Van den Burg (1985)
	K	Seedlings in sand culture			0.2-0.3	0.3-0.5	0.5-0.7	0.7-1.0			McGee (1969)
		Seedlings in pot trial				0.43					McKee (1978)
		Seedlings in pot trial			0.10-0.20	> 0.20					Terman and Bengtson (1973)
		Young plants (4yrs)		0.25	0.25-0.30	0.30-0.35	0.35-0.40				Bengtson (1976)
		Nursery crop				1.38					Donald and Young (1982)
		Young plantations				0.21-0.86					White and Mead (1971)
		Plantations		< 0.3							Reuter and Robertson (1993)
		Plantations				0.26					Anon. (1997)
		Young stands				0.38-1.18					Van den Burg (1985)
		Young stands			0.20	0.24-0.32					Shoulders and Tiarks (1980)
		Young stands		0.25	0.25-0.30	> 0.30					Van den Burg (1985)
		Toung stands		0.30-0.35	0.40-0.50	0.50-0.90					Van den Burg (1985)
	Ca	Seedlings in pot trial				0.28					McKee (1978)
		Young plants				0.15					Bengtson (1976)
		Nursery crop				0.43					Donald and Young (1982)
		Young plantations				0.12-0.40					White and Mead (1971)
		Young plantations		< 0.12							Reuter and Robertson (1993)
		Plantations				0.13					Anon. (1997)
		Plantations				0.10-0.14					Van den Burg (1985)
		Young stands		0.13	0.13-0.15	> 0.15					Van den Burg (1985)
	Mg	Seedlings in pot trial				0.15					McKee (1978)
		Young plants (4yrs)				0.09					Bengtson (1976)
		Nursery crop				0.16					Donald and Young (1982)
		Young plantations				0.06-0.15					White and Mead (1971)
		Plantations				0.10-0.11					Van den Burg (1985)
		Plantations		< 0.80							Reuter and Robertson (1993)
						0.08					Anon. (1997)
		Young stands			0.04	0.05-0.13					Van den Burg (1985)
		Young stands		0.04	0.04-0.08	> 0.08					Van den Burg (1985)
	S	Young plants (4yrs)				0.09					Bengtson (1976)
		Young plants (4yrs)				0.08-0.12					Anon. (1997)
		Plantations				0.08-0.10					Lambert and Turner (1977)
	Cu	Nursery crop				3.4					Donald and Young (1982)
		Young plantations	1.5-2.8			2.1-3.8					White and Mead (1971)
		Plantations				3.0-4.0					Van den Burg (1985)
		Plantations		< 2		2-18					Reuter and Robertson (1993)
		Young stands				2.7-4.5					Van den Burg (1985)
		Stands				6.1-15					Van den Burg (1985)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. elliottii	Zn	Seedlings				47-52					McKee (1978)
		Nursery crop				18					Donald and Young (1982)
		Plantations				49-56					Van den Burg (1985)
		Plantations		6-10		10-68					Reuter and Robertson (1993)
						15-57					Van den Burg (1985)
	B	Seedlings	< 1.9								Reuter and Robertson (1993)
		Seedlings	< 1.9								Reuter and Robertson (1993)
		Young stands	9-10	10		10-21					Van den Burg (1985)
		Young stands				11-33					Van den Burg (1985)
						16-32					Lambert and Turner (1977)
			4-10	10		10-28					Anon. (1997)
		Plantations				4-10					Van den Burg (1985)
	Fe	Nursery crop				201					Donald and Young (1982)
		Young plantations				34-220					White and Mead (1971)
		Plantations				35					Anon. (1997)
		Plantations				65-404					Reuter and Robertson (1993)
	Mn	Nursery crop				193					Donald and Young (1982)
		Young plantations				13-496					White and Mead (1971)
		Young plantations						3500			Berlin (this study)
		Plantations				92-118					Van den Burg (1985)
		Plantations				10-20					Anon. (1997)
		Plantations			21	284					Reuter and Robertson (1993)
		Young stands				151-506					Van den Burg (1985)
		Young stands				240-749					Van den Burg (1985)
		Stands				340-1030					Van den Burg (1985)
											Van den Burg (1985)
											Van den Burg (1985)
P. palustris	N	Young plants (4yrs)				1.06					Bengtson (1978)
		Young plants (4yrs)				0.85-1.01					McLeod *et al.* (1979)
	P	Young plants (4yrs)				0.11					Bengtson (1978)
		Young plants (4yrs)				0.09-0.12					McLeod *et al.* (1979)
	K	Seedlings		< 0.3	0.35-0.40						Reuter and Robertson (1993)
		Young plants (4yrs)		0.25	0.25-30	0.30-0.35	0.35-0.40				Bengtson (1978)
		Young plants (4yrs)				0.50-0.65					McLeod *et al.* (1979)
	Ca	Young plants (4yrs)				0.18					Bengtson (1978)
		Young plants (4yrs)				0.19-0.37					McLeod *et al.* (1979)
	Mg	Young plants (4yrs)				0.10					Bengtson (1978)
		Young plants (4yrs)				0.05-0.11					McLeod *et al.* (1979)
	S	Young plants (4yrs)				0.10					Bengtson (1978)
	Cu	Seedlings				28-33					Stone (1965)
	Zn	Seedlings				12-40					Stone (1965)
						33					Stone (1965)
	B	Seedlings				7-12					Stone (1965)
		Young plantations		< 8							Reuter and Robertson (1993)
	Fe					59					Stone (1965)
	Mn					119-345					Stone (1965)
						170-334					Stone (1965)
	Mo	seedlings				0.10-0.12					Stone (1965)
P. patula	N	Seedlings in pot trial	0.67			0.85-1.00	> 1.00				Buchler (1997)
		Nursery crop				1.92					Donald and Young (1982)
		Plantations			1.52		2.15	2.58			Schutz (1989)
		Plantations				1.9-2.0					Vail *et al.* (1961)
		Young stands				1.68-2.13					Van den Burg (1985)
		Young stands				1.92-2.20					Singh (1982)
		Stands			1.1	1.9-2.5					Grey *et al.* (1979)
		Adult stands				1.57					Singh (1982)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. patula	P	Seedlings in pot trial				0.11-0.15	> 0.15				Buchler (1997)
		Nursery crop				0.30					Donald and Young (1982)
		Plantations				0.17-0.23					Vail *et al.* (1961)
		Plantations					0.13	0.26			Schutz (1989)
		Young stands			0.08-0.10	0.10-0.18					Van den Burg (1985)
		Young and adult stands				0.14-0.17					Singh (1982)
		Stands			0.04	0.25-0.49					Grey *et al.* (1979)
	K	Seedlings in pot trial				0.54-0.78					Buchler (1997)
		Nursery crop				1.25					Donald and Young (1982)
		Plantations				1.01-1.06					Vail *et al.* (1961)
		Plantations			0.46	0.87	1.32				Schutz (1989)
		Young stands	0.32	0.35		0.36-1.06					Van den Burg (1985)
		Young and adult stands				0.70-0.89					Singh (1982)
		Young and adult stands				0.39-0.55					Singh (1982)
		Stands			0.24	0.47-0.78					Grey *et al.* (1979)
	Ca	Seedlings in pot trial			0.26	0.35-0.45	0.45-0.55				Buchler (1997)
		Nursery crop				0.41					Donald and Young (1982)
		Plantations				0.27-0.41					Vail *et al.* (1961)
		Plantations			0.0.6	0.26-0.61					Schutz (1989)
		Young stands				0.21-0.43					Van den Burg (1985)
		Stands				0.07-0.65					Grey *et al.* (1979)
	Mg	Seedlings in pot trial			0.14	0.14-0.20					Buchler (1997)
		Nursery crop				0.23					Donald and Young (1982)
		Plantations				0.18-0.19					Vail *et al.* (1961)
		Plantations			0.08	0.17					Schutz (1989)
		Young stands			0.04	0.07-0.14					Van den Burg (1985)
		Young stands				0.15-0.36					Singh (1982)
		Stands				0.03-0.17					Grey *et al.* (1979)
		Adult stands				0.57					Singh (1982)
	S	Plantations				0.10-0.16					Vail *et al.* (1961)
		Stands				0.06-0.15					Grey *et al.* (1979)
						0.11-0.17					Lambert and Turner (1977)
	Cu	Seedlings in pot trial				9-14					Buchler (1997)
		Nursery crop				3.7					Donald and Young (1982)
		Plantations				8-9					Vail *et al.* (1961)
		Plantations			2	5		30			Schutz (1989)
		Young stands				3.0-5.1					Van den Burg (1985)
		Young stands			2.8						Van den Burg (1985)
	Zn	Seedlings in pot trial				35-50					Buchler (1997)
		Nursery crop				22					Donald and Young (1982)
		Plantations			28	41					Vail *et al.* (1961)
		Plantations			15	25-43					Schutz (1989)
		Young stands				12-38					Van den Burg (1985)
		Stands				16-45					Grey *et al.* (1979)
	B	Seedlings in pot trial			9	10-40			> 70		Buchler (1997)
		Plantations	7			14					Vail *et al.* (1961)
		Plantations			10	24-38					Schutz (1989)
		Young stands	6	10		12-24					Van den Burg (1985)
		Young stands	8-18	16		14-53					Van den Burg (1985)
						8-18					Lambert and Turner (1977)
	Fe	Seedlings in pot trial			23-33	50-155					Buchler (1997)
		Nursery crop				306					Donald and Young (1982)
		Plantations				148-245					Vail *et al.* (1961)
		Plantations			36	113	291				Schutz (1989)
		Young stands				98-223					Van den Burg (1985)
		Stands				97-274					Grey *et al.* (1979)
						22					Van den Burg (1985)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. patula	Mn	Seedlings in pot trial			281	300-770					Buchler (1997)
		Nursery crop				191					Donald and Young (1982)
		Young plantations						3000	> 8000		Berlin (this study)
		Young plantations						1300-1900			London (this study)
		Plantations						> 2000			Van den Burg (1985)
		Plantations				276-1308		2790			Schutz (1989)
		Plantations				296-400					Vail *et al.* (1961)
		Young stands				249-701					Van den Burg (1985)
		Stands				86-116					Grey *et al.* (1979)
						200					Stone (1968)
	Mo	Seedlings in pot trial	< 0.01		0.04						Buchler (1997)
											Van den Burg (1985)
P. pinaster	N	Seedlings in pot trial	0.75-0.90	1.0	1.1-1.3	1.3-1.5	1.5-1.8				Nakos (1980)
		Seedlings in pot trial	0.75-0.90		1.1	1.52	1.52-2.0				Nakos (1980)
		Young stands		0.78	1.02	1.15					Van den Burg (1985)
		Young stands		0.4-0.9		0.09-0.14					Keay (1964)
					< 0.9	0.9-1.2	> 1.2				Van den Burg (1985)
		Plantations			0.39-0.60		0.60-0.90				Reuter and Robertson (1993)
	P	Seedlings in pot trial	0.09-0.10			0.10-0.25					Nakos (1980)
		Seedlings in pot trial	0.05-0.09	0.10		0.10-0.14					Nakos (1980)
		Young stands		0.05		0.11					Keay (1964)
		Plantations			0.054-0.056	0.06-0.08	0.10-0.20				Reuter and Robertson (1993)
	K	Seedlings in pot trial	1.2			2.1					Nakos (1980)
		Young stands				0.59-0.83					Keay (1964)
					< 0.40	0.40-0.50	> 0.50				Van den Burg (1985)
		Plantations				0.25-0.80					Reuter and Robertson (1993)
	Ca	Young plantations				0.20-0.29					Van den Burg (1985)
		Plantations				0.35-2.33					Reuter and Robertson (1993)
		Young stands				0.27					Van den Burg (1985)
	Mg	Young plantations				0.12-0.19					Van den Burg (1985)
		Young stands				0.14					Van den Burg (1985)
					< 0.05	0.05-0.11	> 0.11				Van den Burg (1985)
		Plantations				0.16-0.22	0.25-1.61				Reuter and Robertson (1993)
	S	Plantations				0.05-0.16					Reuter and Robertson (1993)
	Cu	Young plantations				6-31					Van den Burg (1985)
		Young plantations			3.4						Reuter and Robertson (1993)
		Plantations	< 3		3.4	4.0-19.0				> 81	Reuter and Robertson (1993)
	B	Young stands	5-6	7		16					Stone and Will (1965)
			5-6								Stone (1965)
				15							Will *et al.* (1963)
		Plantations		5-6		16					Reuter and Robertson (1993)
	Mn	Young plantations				80.4					Reuter and Robertson (1993)
	Zn	Young plantations			36.0						Reuter and Robertson (1993)
		Plantations		< 10		10.0-40.0				> 61	Reuter and Robertson (1993)
	Fe	Plantations		24		65-217				> 404	Reuter and Robertson (1993)
	Mn	Plantations		7.0-10.0		14-427					Reuter and Robertson (1993)
P. radiata	N	Seedlings on nutrient solution	1.1-1.6	1.6		1.6-4.0					Will (1961)
		Seedlings on nutrient solution		0.38-0.52			1.84				Will (1977)
		Seedlings in nutrient solution	0.5-1.0		1.0-1.2	1.6-2.4				> 2.6	Reuter and Robertson (1993)
		Seedlings on sand culture			0.9	1.3-2.1					Van den Driessche (1979)
		Seedlings in pot trial	0.75-0.90	1.0	1.1-1.4	1.4-1.7	> 1.7				Nakos (1980)
		Seedlings in pot trial	0.75-0.9		1.1	1.76	1.76-2.0				Nakos (1980)
		Seedlings in pot trial				1.5-1.9					Nakos (1979)
		Seedlings in pot trial				1.6					Reuter and Robertson (1993)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. radiata	N	Seedlings in nursery				1.32-1.75					Flinn *et al.* (1980)
		Seedlings in nursery				1.44-3.59					Knight (1980)
		Seedlings		0.5-0.9	1.0-1.2	1.9-2.4				> 2.6	Reuter and Robertson (1993)
		Nursery crop				2.02					Donald and Young (1982)
		Nursery crop				1.14-1.74					Flinn *et al.* (1980)
		Nursery crop					> 1.5				Hopman and Flinn (1983)
		Nursery crop				> 1.4					Knight (1978)
		Nursery crop			0.99-1.27	1.50-1.94					Knight (1978)
		Young plants (4yrs)				1.22-1.39					Knight (1978)
		Nursery crop		1.2	1.2-1.5	> 1.5					Will (1978)
		Young plantations			< 1.4						Celliar and Stephens (1980)
		Young plantations	< 1.0	1.2		1.2-2.5			> 2.5		Lewis and Ferguson (1993)
		Young plantations				1.98-2.05					DeBell and Radwan (1984)
		Young plantations				1.47-2.33					Ruiter (1968)
		Young plantations			1.08-1.28	1.34-1.36	1.73-1.89				Stone and Will (1965)
		Young plantations			1.26	1.47-1.63					Will and Hodgkiss (1977)
		Young plantations		< 1.0	1.0-1.2	1.2-2.0		>2.1			Reuter and Robertson (1993)
		Plantations				1.2-1.4					Anon. (1997)
		Young stands				1.38-1.68	1.51-1.83				Ballard (1978)
		Young stands				1.49					Ballard and Will (1978)
		Young stands				1.04-1.71					Flinn *et al.* (1979)
		Young stands				1.17-1.34					Flinn *et al.* (1979)
		Young stands				1.16-1.60					Hunter and Graham (1980)
		Young stands-open canopy			< 1.2						Miller (1981)
		Young stands-closed canopy			< 1.4						Miller (1981)
		Young stands (3yrs)				1.46-2.48					Ruiter (1968)
		Young stands			< 1.0						Schutz (1976)
					< 1.2	1.2-1.5	> 1.5				Mead *et al.* (1981)
		Adult stands				1.26-1.38					Ballard and Will (1981)
	P	Seedlings on nutrient solution	0.06-0.10	0.10	0.10-0.14	0.14-0.63					Will (1961)
		Seedlings on nutrient solution					0.22				Will (1977)
		Seedlings in nutrient solution	0.055-0.090		0.09-0.14	0.177-0.344					Reuter and Robertson (1993)
		Seedlings in pot trial				0.05-0.08					Van den Burg (1985)
		Seedlings in pot trial	0.07-0.09	0.10		0.10-0.14					Nakos (1980)
		Seedlings in pot trial	0.09-0.10			0.10-0.32					Nakos (1980)
		Seedlings in pot trial			0.11-0.14	0.17-0.21					Nakos (1979)
		Seedlings in nursery				0.13-0.27					Flinn *et al.* (1980)
		Nursery crop				0.38					Donald and Young (1982)
		Nursery crop					> 0.15				Hopmans and Flinn (1983)
		Seedlings in nursery				0.22-0.53					Knight (1975)
		Nursery crop				0.13-0.19	0.15-0.27				Flinn *et al.* (1980)
		Nursery crop (1yr)				> 0.12					Knight (1978)
		Nursery crop (2yrs)			0.10	0.12-0.20					Knight (1978)
		Nursery crop (3yrs)				0.19-0.30					Will (1961)
		Young plants (4yrs)				0.12-0.13					Knight (1978)
		Nursery crop		0.12	0.12-0.14	> 0.14					Will (1978)
		Young plantations			< 0.14						Cellier and Stephen (1980)
		Young plantations		< 0.12		> 0.12					Lewis and Ferguson (1993)
		Young plantations				0.18-0.21					Turvey (1984)
		Young plantations			0.05-0.06	0.10-0.12					Ruiter (1968)
		Young stands (3yrs)			0.04-0.05	0.10-0.12					Ruiter (1968)
		Young plantations			< 0.08	0.09-0.16					Stone an Will (1965)
		Young plantations	< 0.10	0.12	0.10-0.14	0.14-0.30				> 0.8	Reuter and Robertson (1993)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. radiata	P	Plantations		< 0.10	0.10-0.14	014-0.30				> 0.8	Reuter and Robertson (1993)
		Plantations				0.10					Anon. (1997)
		Young stands					0.12-0.14				Ballard (1978)
		Young stands			0.07	0.10-0.14					Ballard (1978)
		Young stands				0.16					Ballard and Will (1981)
		Young stands			< 0.11	0.14					Flinn and Aeberli (1982)
		Young stands			0.07-0.11	0.10-0.22					Flinn *et al.* (1979)
		Young stands	0.09			0.12-0.15					Flinn *et al.* (1982)
		Young stands	0.07-0.09			0.10-0.14					Flinn *et al.* (1979)
		Young stands			0.06-0.07	0.07-0.12	> 0.12				Gentle *et al.* (1965)
		Young stands			0.06-0.12	0.10-0.21					Hunter and Graham (1982)
		Young stands			< 0.12	>0.12					Mead and Gadgil (1970)
		Young stands			< 0.12						Miller (1981)
		Young stands			< 0.10						Schutz (1976)
		Young stands			0.10-0.12	0.12-0.14	> 0.14				Truman and Humphreys (1985)
		Young stands			0.09	0.13-0.14					Will and Hodgkiss (1977)
				< 0.12	0.12-0.14	> 0.14					Mead (1981)
		Stands			0.17						Van den Burg (1985)
		Young to adult stands			0.06-0.09	0.09-0.23					Van den Burg (1985)
		Adult stands				0.19-0.20					Ballard and Will (1981)
	K	Seedlings on nutrient solution	0.2-0.7	0.9		1.1-3.4					Will (1961)
		Seedlings on nutrient solution					1.01				Will (1977)
		Seedlings in nutrient solution	< 0.25		0.35	0.26-1.8					Reuter and Robertson (1993)
		Seedlings in pot trial				0.48-0.65					Van den Burg (1985)
		Seedlings in pot trial	1.2			1.7					Nakos (1980)
		Seedlings in pot trial				1.3-1.6					Nakos (1979)
		Seedlings in nursery			0.57-0.75	0.82-1.42					Flinn *et al.* (1980)
		Seedlings in nursery				0.59-0.84					Knight (1975)
		Seedlings		0.7		0.7-1.1					Van den Burg (1985)
		Seedlings	0.7-1.1								Will (1961)
		Seedlings	0.3-0.5			0.9-1.2					Will (1961)
		Nursery crop				1.74					Donald and Young (1982)
		Nursery crop				0.57-0.72	0.82-1.42				Flinn *et al.* (1980)
		Nursery crop					> 0.90				Hopmans and Flinn (1983)
		Nursery crop (1yr)				> 0.85					Knight (1978)
		Nursery crop (2yrs)			0.31	0.42-1.08					Knight (1978)
		Nursery crop				1.07-1.32					Will (1961)
		Young plants (4yrs)				0.73-1.02					Knight (1978)
		Nursery crop		0.3	0.3-0.5	> 0.5					Will (1978)
		Very young stands				0.67-0.80					Flinn *et al.* (1979)
		Young plantations			< 0.35						Cellier and Stephen (1980)
		Young plantations		<0.25	0.3	0.40-0.45					Lewis and Ferguson (1993)
		Young plantations				0.43-0.71					Ruiter (1968)
		Young plantations				0.77-0.89					Turvey (1984)
		Plantations		< 0.35	0.35-0.50	> 0.5					Reuter and Robertson (1993)
		Plantations				0.30					Anon. (1997)
		Young stands				0.87-1.07					Will and Hodgkiss (1977)
		Young stands			0.21-0.28	0.49-0.85					Ballard (1978)
		Young stands				0.93					Ballard and Will (1981)
		Young stands				0.53-1.11					Flinn *et al.* (1979)
		Young stands				0.44-1.15					Gentle *et al.* (1965)
		Young stands				0.91-1.18					Hunter and Graham (1982)
		Young stands			< 0.40						Mead and Gadgil (1978)
		Young stands			<0.25						Schutz (1976)
		Young stands				0.51-1.18					Stone and Will (1965)
					< 0.3	0.3-0.5	> 0.5				Mead *et al.* (1981)
		Stands				0.27					Van den Burg (1985)
		Stands				0.83					Van den Burg (1985)
		Young to adult stands				0.32-1.03					Humphreys (1964)
		Adult stands				1.03-1.10					Ballard and Will (1981)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. radiata	Ca	Seedlings on nutrient solution				0.04-0.61					Will (1961)
		Seedlings on nutrient solution					0.25				Will (1977)
		Seedlings in pot trial				0.54-1.38					Van den Berg (1985)
		Seedlings in pot trial				0.56-0.86					Nakos (1979)
		Seedlings in nursery				0.17-0.53					Flinn *et al.* (1980)
		Seedlings in nursery				0.13-0.31					Knight (1975)
		Nursery crop					0.17-0.53				Flinn *et al.* (1980)
		Nursery crop					> 0.15				Hopmans and Flinn (1983)
		Nursery crop (1yr)				0.23-0.83					Knight (1978)
		Nursery crop (2yrs)				0.18					Donald and Young (1982)
		Nursery crop				> 0.10					Knight (1978)
		Nursery crop (3yrs)				0.08-0.20					Will (1961)
		Nursery crop		0.10	0.10	> 0.10					Will (1977)
		Young plantations				0.32-0.49					Knight (1978)
		Young plantations				0.18-0.41					Ruiter (1968)
		Young plantations			< 0.10	> 0.10					Lewis and Ferguson (1993)
		Young plantations				0.18-0.20					Turvey (1984)
		Young plantations		< 0.06	0.06-0.07	0.08-0.45					Reuter and Robertson (1993)
		Plantations		< 0.06	0.06-0.07	0.08-0.45					Reuter and Robertson (1993)
		Plantations				0.15					Anon. (1997)
		Very young stands				0.22-0.29					Flinn *et al.* (1979)
		Young stands				0.17-0.29					Ballard (1978)
		Young stands				0.24					Ballard and Will (1981)
		Young stands			0.12-0.17	0.15-0.31					Flinn *et al.* (1979)
		Young stands				0.17-0.34					Gentle *et al.* (1965)
		Young stands				0.17-0.23					Hunter and Graham (1982)
		Young stands			< 0.20						Schutz (1976)
		Young stands				0.16-0.30					Will and Hodgkiss (1977)
					< .01		> .01				Mead *et al.* (1981)
		Young to adult stands			0.5-0.11	0.11-0.35					Van den Burg (1985)
		Adult stands				0.10-0.17					Ballard and Will (1981)
	Mg	Seedlings on nutrient solution					0.11				Van den Burg (1985)
		Seedlings on nutrient solution		0.08	0.08-0.11	0.11-0.61					Will (1961)
		Seedlings on nutrient solution					0.14				Will (1977)
		Seedlings in nutrient solution	< 0.07		0.07-0.10	0.11-0.80					Reuter and Robertson (1993)
		Seedlings in sand culture		0.08	0.08-0.11	0.11					Van den Burg (1985)
		Seedlings in pot trial				0.10-0.14					Van den Burg (1985)
		Seedlings in pot trial				0.20-0.24					Nakos (1979)
		Seedlings in pot trial			0.08-0.11						Flinn *et al.* (1980)
		Seedlings in pot trial				0.14-0.25					Knight (1975)
		Seedlings in pot trial		< 0.07	0.06-0.08	0.10-0.40					Reuter and Robertson (1993)
		Nursery crop				0.10					Donald and Young (1982)
		Nursery crop				0.08-0.11					Flinn *et al.* (1980)
		Nursery crop				>0.06					Knight (1978)
		Nursery crop (1yrs)					> 0.12				Hopmans and Flinn (1983)
		Nursery crop (2yrs)			0.06-0.07	0.08-0.12					Knight (1978)
		Nursery crop (3yrs)	0.09		0.11-0.12	0.12-0.16					Will (1961)
		Nursery crop		0.07	0.07-0.10	> 0.10					Will (1977)
		Young plants		0.06		0.09-0.14					Knight (1978)
		Very young stands				0.11-0.14					Flinn *et al.* (1979)
		Young plantations				0.08-0.16					Ruiter (1968)
		Young plantations			< 0.08	> 0.08					Lewis and Ferguson (1993)
		Young plantations			< 0.08	0.09-0.19					Stone and Will (1965)
		Young plantations				0.11-0.14					Turvey (1984)
		Plantations		< 0.05	0.06-0.08	0.10-0.40					Reuter and Robertson (1993)
		Plantations				0.07					Anon. (1997)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. radiata	Mg	Young stands					0.23-0.46				Ballard (1978)
		Young stands				0.10					Ballard and Will (1981)
		Young stands				0.23-0.34					Flinn *et al.* (1979)
		Young stands				0.15-0.31					Gentle *et al.* (1965)
		Young stands				0.11-0.15					Hunter and Graham (1982)
		Young stands			< 0.06						Mead and Gadgil (1978)
		Young stands			< 0.10						Schutz (1976)
		Young stands				0.07-0.10					Will and Hodgkiss (1977)
		Stands				0.13					Van den Burg (1985)
		Stands		0.06	0.06-0.08	0.08					Leaf (1968)
		Stands			< 0.07	0.07-0.10	> 0.10				Mead *et al.* (1981)
		Young to adult stands				0.06-0.43					Van den Burg (1985)
		Adult stands				0.02-0.09					Ballard and Will (1981)
	S	Seedlings in nursery				0.10-0.14					Flinn *et al.* (1980)
		Seedlings in pot trial				0.13-0.16					Nakos (1979)
		Nursery crop (SO_4-S)			0.014-0.017	0.028-0.057					Flinn *et al.* (1980)
		Nursery crop				> 0.12					Knight (1978)
		Nursery crop				0.13-0.18					Nakos. (1979)
		Young plantations				0.10-0.12					Ruiter (1968)
		Young plantations			< 0.12	> 0.13					Reuter and Robertson (1993)
	SO_4-S	Young plantations		< 80	124-400	> 400					Reuter and Robertson (1993)
	S	Plantations			< 0.12	> 0.13					Reuter and Robertson (1993)
		Plantations				0.1-0.2					Anon. (1997)
	SO_4-S	Plantations		< 80	125-400	> 400					Reuter and Robertson (1993)
		Stands				0.6-0.15					Van den Burg (1979)
		Stands	0.008	0.008-0.02	0.02	0.04	> 0.04				Lambert and Turner (1977)
		Stands	0-0.008	0.008	0.008-0.02	0.02-0.04	0.04	> 0.04			Lambert *et al.* (1981)
		Adult stands	0-0.008	0.008	0.008-0.02	0.02	0.04	> 0.04			Turner (1979)
	Cu	Nursery crop				5.9-14.9					Flinn *et al.* (1980)
		Nursery crop	1.2-1.5			2.0-4.5					Knight (1975)
		Nursery crop (1yrs)				3.8					Donald and Young (1982)
		Nursery crop (2yrs)				3.6-8.6		24.0			Knight (1978)
		Nursery crop				> 2					Knight (1978)
		Nursery crop		2	2-4	> 4					Will (1978)
		Young plants				3.7-4.1					Knight (1978)
		Very young stands				4.3-6.4					Flinn *et al.* (1979)
		Young plantations				3.2-3.8					Celliers and Stephens (1980)
		Young plantations		< 2	4	2.5	> 20		> 50		Lewis and Ferguson (1993)
		Young plantations				1-3					Ruiter (1968)
		Plantations		< 2.0	2.1-2.3	2.4-9.0				> 40	Reuter and Robertson (1993)
		Plantations				2					Anon. (1997)
		Young stands (3yrs)				2-3					Ruiter (1968)
		Young plantations	2.6-3	3-4		4-4.3					Turvey (1984)
		Young plantations		< 2	2.1-2.3	2.4-9.0					Reuter and Robertson (1993)
		Young stands				6.6-9.0					Flinn *et al.* (1979)
		Young stands			< 2.5	> 2.5					Mead and Gadgil (1978)
				2		2-12					Van den Burg (1985)
					2.9-3.7	3.8-9.0					Van den Burg (1985)
		Adult stands				5.4-5.5					Ballard an Will (1981)
	Zn	Seedlings in pot trial		8-9		> 12					McGrath and Robson (1985)
		Seedlings in nursery			19-25	29-45					Flinn *et al.* (1980)
		Seedlings in nursery				15-22					Knight (1975)
		Seedlings	< 6		11-12						Reuter and Robertson (1993)
		Seedlings			11-12						Reuter and Robertson (1993)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. radiata	Zn	Young plants				48-78					Knight (1978)
		Nursery crop				56					Donald and Young (1982)
		Nursery crop			19	25-45					Flinn *et al.* (1980)
		Nursery crop					>25				Hopmans and Flinn (1983)
		Nursery crop (1yrs)				> 5					Knight (1978)
		Nursery crop (2yrs)				20-82					Knight (1979)
		Nursery crop				32					Van den Burg (1985)
		Nursery crop		10	10-20	> 20					Will (1978)
		Young plantations				33-58					Celliers and Stephens (1980)
		Plantations		< 11	11-13	14-64		> 200			Reuter and Robertson (1993)
		Plantations				15					Anon. (1997)
		Very young stands				34-60					Flinn *et al.* (1979)
		Young stands	8-13		15-17	19-21					Ruiter (1968)
		Young plantations				8-21					Ruiter (1968)
		Young plantations		< 10	12	10	>20		> 150		Lewis and Ferguston (1993)
		Young plantations		< 11	11.0-13.0	14-60				> 200	Reuter and Robertson (1993)
		Plantations			10						Reuter and Robertson (1993)
		Young stands	5-7	10-12		14-23					Van den Burg (1985)
		Young stands				23-38					Flinn *et al.* (1979)
		Young stands		5	5-11	19					Van den Burg (1985)
		Young stands		5							Van den Burg (1985)
		Young stands	1-5	5	5-11	10-125					Van den Burg (1985)
		Young stands				30-54					Van den Burg (1985)
		Stands				50					Van den Burg (1985)
		Adult stands				39-41					Ballard an Will (1981)
	B	Seedlings in pot trial	3-6	4-6	4-6	6-8	8-25				Snowdon (1982)
		Seedlings in nursery				11-15					Flinn *et al.* (1980)
		Nursery crop				> 8					Knight (1978)
		Nursery crop				8-22					Knight (1979)
		Nursery crop		8	8-12	> 12					Will (1978)
		Young plants				17-32					Knight (1978)
		Young plantations				12-17					Flinn *et al.* (1980)
		Young plantations		< 8	12	12	100		> 150		Lewis and Ferguson (1993)
		Young plantations		8	8-12	11-38		> 4-101			Hopmans and Flinn (1983)
		Young plantations				12-21					Ruiter (1966)
		Plantations		3-12							Lambert *et al.* (1981)
		Plantations	<5	12	10.0-16.0	16-70		> 70		> 170	Reuter and Robertson (1993)
		Plantations				8-10					Anon. (1997)
		Young stands	7-8			11-31					Ballard (1978)
		Young stands				48-60					Flinn *et al.* (1979)
		Young stands			<9	>12					Mead and Gadgil (1978)
		Young stands		8							Miller (1981)
		Young stands	3-7	7		8-13					Stone and Will (1965)
		Young stands				27					Cromer (1980)
		Young stands		10-15							Van den Burg (1985)
		Young stands		8	8-12						Lambert and Turner (1977)
		Young stands			< 8	8-12	> 12				Mead *et al.* (1981)
		Young stands	3-9			11-61					Stone (1968)
		Trees		4-6	4-6	> 6					Snowdon (1982)
		Trees		15							Will *et al.* (1963)
		Adult stands				7-17					Ballard an Will (1981)
		Adult stands		6-15							Turner (1979)
	Fe	Seedlings on nutrient solution		35	35-45						Ruiter (1983)
		Seedlings on nutrient solution				40-50					Stone (1968)
		Seedlings on nutrient solution				10-90					Will (1961)
		Seedlings in nutrient solution	< 35		40-80	70-200					Reuter and Robertson (1993)
		Seedlings in nursery				85-290					Flinn *et al.* (1980)
		Seedlings in pot trial	56-88		76-90	122					Nakos (1979)
		Nursery crop				71					Donald and Young "(1982)
		Nursery crop				85-290					Flinn *et al.* (1980)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. radiata	Fe	Nursery crop				97-499					Knight (1978)
		Nursery crop				> 24-40					Knight (1978)
		Nursery crop					>100				Hopmans and Flinn (1983)
		Very young stands				75-155					Flinn *et al.* (1979)
		Young plantations				81-116					Celliers and Stephens (1980)
		Young plantations		< 4	55	350					Van den Burg (1985)
		Young plantations				58-116					Ruiter (1968)
		Plantations		< 35	40-70	70-200					Reuter and Robertson (1993)
		Plantations				40-60					Anon. (1997)
		Young stands				132-176					Flinn *et al.* (1979)
		Young stands				194-421					Gentle *et al.* (1965)
						21-52					Stone (1968)
		Young to adult stands				71-435					Van den Burg (1985)
	Mn	Seedlings on nutrient solution				140-800					Stone (1968)
		Seedlings on nutrient solution				120-420					Will (1961)
		Seedlings in nutrient solution	< 5.0		5.0-20.0	20-400					Reuter and Robertson (1993)
		Seedlings in nutrient solution				40-70					Reuter and Robertson (1993)
		Seedlings in pot trial				98					Nakos (1979)
		Seedlings in nursery				70	140-350				Flinn *et al.* (1980)
		Seedlings in nursery				156-382					Knight (1978)
		Nursery crop				340					Donald and Young "(1982)
		Nursery crop				70-350	> 50				Flinn *et al.* (1980)
		Nursery crop				>5					Hopmans and Flinn (1983)
		Nursery crop				19-480					Knight (1975)
		Nursery crop				256-361					Knight (1975)
		Young plants		5-10							Knight (1975)
		Young plants		10	10-20	> 20					Ruiter (1983)
		Nursery crop				331-531					Will (1978)
		Very young stands				105-350					Celliers and Stephens (1980)
		Young plantations				148-228					Flinn *et al.* (1979)
		Young plantations		< 10	20	50			> 2500		Lewis and Ferguson (1993)
		Young plantations		< 10.0	11.0-20.0	25-400				> 700	Reuter and Robertson (1993)
		Plantations				77-624					Ruiter (1968)
		Plantations		< 10	11.0-20	24-400				> 700	Reuter and Robertson (1993)
		Plantations				10					Anon. (1997)
		Young stands				34-115					Flinn *et al.* (1979)
		Stands		30							Van den Burg (1985)
		Young to adult stands				126-1100					Van den Burg (1985)
		Adult stands				169-181					Van den Burg (1985)
		Adult stands				220-640					Ballard and Will (1981)
	Mo	Seedlings in nutrient solution	< 0.01-0.02		0.02-0.06	0.06-0.40					Reuter and Robertson (1993)
		Young plantations				0.3-1.4					Stone (1968)
						0.03-0.05					Ruiter (1966)
		Young plantations		< 0.05		> 0.05					Anon. (1997)
		Plantations				0.03-0.05					Lewis and Ferguson (1993)
P.taeda	N	Seedlings in nutrient solution			0.93-0.97	1.44-1.99					Van den Burg (1985)
		Seedlings on sand culture			< 1.2	1.2-1.7	1.7-2.3	> 2.3			Fowells and Krauss (1959)
		Seedlings in pot trial				1.45	1.45-1.97				Van den Burg (1985)
		Seedlings in pot trial			1.04	2.3-2.84					Pharis and Kramer (1964)
		Seedlings in pot trial		1.2			1.7-2.3				Van den Burg (1985)
		Seedlings in pot trial		1.38-1.89							Reuter and Robertson (1993)
		Seedlings				1.45-1.56					Hook *et al.* (1983)
		Young plants (4yrs)				1.31					Bengtson (1976)
		Nursery crop				1.86					Donald and Young (1982)
		Young plantations	0.58-0.87		0.90-1.10	1.18-1.38					Bengtson and Mays (1978)
		Young plantations		0.74		1.70					London
		Young plantations				0.64-0.86					Carter *et al.*(1984)
		Young plantations				0.97					Haines and Haines (1979)
		Young plantations				1.12-1.2					Van den Burg (1985)
		Young plantations			1.08-1.22	1.29-1.34					Van den Burg (1985)
		Young plantations			1.05-1.2	1.2-1.4					Van den Burg (1985)
		Young plantations			1.1-1.3	1.3-1.6	> 1.6				Van den Burg (1985)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. taeda	N	Plantations				1.7-2.2					Vail *et al.* (1961)
		Plantations		< 0.1	1.0	1.03					Reuter and Robertson (1993)
		Plantations				1.1					Anon. (1997)
		Young stands			< 1.2						Cromerford and Fisher (1984)
		Young stands				1.2					Van den Burg (1985)
		Young stands				0.98-1.18					Pope (1979)
		Young stands				1.05-1.30					Van den Burg (1985)
		Young stands					1.78-2.35				Van den Burg (1985)
		Young stands			< 1.06	1.45-1.96					Schutz (1976)
				1.01-1.1	1.0-1.4	1.3-2.2		> 2.0			Van den Burg (1985)
		Young stands (15yrs)			< 0.95	>0.95					Cromerford and Fisher (1984)
		Stands (20yrs)			< 0.7	> 0.95					Cromerford and Fisher (1984)
		Stands (20yrs)			1.05	1.24-1.29					Van den Burg (1985)
		Young and adult stands			1.0	1.43					Lea and Ballard (1982)
	P	Seedlings on sand culture			< 0.10	0.10-0.14	0.14-0.18	0.18-0.62			Fowells and Krauss (1959)
		Seedlings in pot trial				0.09	0.09-0.11				Van den Burg (1985)
		Seedlings in pot trial				0.17-0.23					Hook *et al.* (1983)
		Seedlings in pot trial		0.10			0.14-0.15				Van den Burg (1985)
		Seedlings in pot trial			< 0.07						Terman and Bengtson (1973)
		Seedlings in pot trial			< 0.07						Terman and Nelson (1973)
		Seedlings	< 0.11								Reuter and Robertson (1993)
		Young plants (4yrs)				0.13					Bengston (1976)
		Young plants (4yrs)				0.15-0.18					Gilmore and Motis (1981)
		Nursery crop				0.25					Donald and Young (1982)
		Young plantations				0.14-0.19					Bengtson and Mays (1978)
		Young plantations				0.08-0.10					Carter *et al.*(1984)
		Young plantations				0.12					Haines and Haines (1979)
		Young plantations			0.09	0.10					McCarthy and Davy (1976)
		Young plantations				0.10-0.12					Wells (1970)
		Young plantations			< 0.10						Wells *et al.* (1970)
		Plantations				0.15-0.22					Vail *et al.* (1951)
		Plantations	< 0.095		0.105	< 0.11					Reuter and Robertson (1993)
		Plantations				0.09-0.10					Anon. (1997)
		Young stands				0.09-0.11					Pope (1979)
		Young stands			0.08-0.11	0.10-0.15	> 0.15				Van den Burg (1985)
		Young stands	0.06	0.06-0.09	0.09-0.10	0.10-0.13	0.13-0.14				Van den Burg (1985)
						> 0.10					Bevage and Richards (1972)
			0.10			0.14-0.18					Van den Burg (1985)
				0.09-0.10	0.06-0.13	0.10-0.30					Van den Burg (1985)
		Stands			0.10	0.12					Van den Burg (1985)
		Young and adult stands			< 0.11						Lea and Ballard (1982)
	K	Seedlings on sand culture				0.79-1.28					Fowells and Krauss (1959)
		Seedlings on sand culture	0.26								Van den Burg (1985)
		Seedlings on sand culture	0.10-0.26								Van den Burg (1985)
		Seedlings on sand culture	0.16-0.25	0.40		0.62					Van den Burg (1985)
		Seedlings in pot trial				1.24-1.28					Hook *et al.* (1983)
		Seedlings in pot trial			0.11-0.20	> 0.20					Terman and Bengtson (1972)
		Seedlings		0.16-0.26							Reuter and Robertson (1993)
		Young plants (4yrs)		0.25	0.25-0.30	0.30-0.35	0.35-0.40				Bengston (1976)
		Young plants (4yrs)			< 0.30	0.30-0.35					Bengston and Smart (1981)
		Nursery crop				1.17					Donald and Young (1982)
		Young plantations				0.44-1.07					Bengtson and Mays (1978)
		Young plantations				0.34-0.46					Carter *et al.*(1984)
		Young plantations				0.61					Haines and Haines (1979)
		Young plantations				0.38-0.39					McCarthy and Davy (1976)
		Young plantations			0.25-0.30	0.30-0.53					Wells (1970)
		Young plantations				0.28-0.53					Wells *et al.* (1970)
		Young plantations		< 0.3		0.35-0.40					Reuter and Robertson (1993)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. taeda	K	Plantations				0.25-0.47					Vail *et al.* (1951)
		Plantations		< 0.30							Reuter and Robertson (1993)
		Plantations				0.26					Anon. (1997)
		Young stands				0.75-1.04					Pope (1979)
		Young stands			<0.36						Schutz (1976)
				0.30-0.35	0.40-0.50	0.50-0.90					Van den Burg (1985)
		Stands				0.31-0.46					Van den Burg (1985)
		Young and adult stands				0.47					Lea and Ballard (1982)
	Ca	Seedlings in nutrient solution			0.01	0.02-0.04					Van den Burg (1985)
		Seedlings on sand culture				0.09-0.25					Fowells and Krauss (1959)
		Seedlings on sand culture		0.03							Van den Burg (1985)
		Seedlings on sand culture		0.03							Van den Burg (1985)
		Seedlings in pot trial				0.20-0.23					Hook *et al.* (1983)
		Seedlings		< 0.0003							Reuter and Robertson (1993)
		Young plants (4yrs)				0.20					Bengston (1976)
		Nursery crop				0.35					Donald and Young (1982)
		Young plantations			0.15-0.20	0.22-0.26					Bengtson and Mays (1978)
		Young plantations				0.36-0.43					Carter *et al.*(1984)
		Young plantations				0.32					Haines and Haines (1979)
		Young plantations				0.17-0.20					McCarthy and Davy (1976)
		Young plantations				0.10-0.19					Wells (1970)
		Plantations				0.29					Vail *et al.* (1951)
		plantations				0.12					Anon. (1997)
		Young stands			< 0.19						Schutz (1976)
						0.12-0.7					Van den Burg (1985)
		Stands				0.09-0.16					Van den Burg (1985)
		Young and adult stands				0.17					Lea and Ballard (1982)
	Mg	Seedlings on sand culture	0.08								Van den Burg (1985)
		Seedlings on sand culture	0.05-0.08								Van den Burg (1985)
		Seedlings on sand culture	0.07								Van den Burg (1985)
		Seedlings in pot trial				0.13-0.15					Hook *et al.* (1983)
		Seedlings			0.06-0.8						Reuter and Robertson (1993)
		Young plants (4yrs)				0.13					Bengston (1976)
		Nursery crop				0.16					Donald and Young (1982)
		Young plantations			0.06-0.08	0.08					Bengtson and Mays (1978)
		Young plantations				0.08-0.10					Carter *et al.*(1984)
		Young plantations				0.07					Haines and Haines (1979)
		Young plantations				0.10-0.11					McCarthy and Davy (1976)
		Young plantations				0.08-0.15					Wells (1970)
		Plantations				0.09-0.13					Vail *et al.* (1951)
		Plantations				0.08					Anon. (1997)
		Young stands			< 0.14	>0.14					Schutz (1976)
		Young stands				0.08-0.13					Van den Burg (1985)
		Stands				0.08-0.12					Van den Burg (1985)
		Young and adult stands				0.12					Lea and Ballard (1982)
	S	Young plants (4yrs)				0.11					Bengtson (1976)
		Plantations				0.16-0.42					Vail *et al.* (1951)
						0.10-0.12					Lambert and Turner (1977)
		Plantations				0.10					Anon. (1997)
	Cu	Seedlings in pot trial				19.0-27.0					Van den Burg (1985)
		Nursery crop				4.9					Donald and Young (1982)
		Young plantations				1.5-3.5					Carter *et al.*(1984)
		Young plantations				1.6-3.3					McCarthy and Davy (1976)
		Young plantations				2.5-3.4					Wells (1970)
		Young plantations				2.5-3.5					Wells (1970)
		Plantations				5-22					Vail *et al.* (1951)
		Plantations			5-22						Reuter and Robertson (1993)
		Plantations				5					Anon. (1997)
		Young stands				5-22					Van den Burg (1985)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
P. taeda	Zn	Seedlings in pot trial				65-215		268-297			Van den Burg (1985)
		Seedlings in pot trial				55-60					Hook *et al.* (1983)
		Seedlings in pot trial				46-107					Van den Burg (1985)
		Nursery crop				23					Donald and Young (1982)
		Young plantations				33-51					Carter *et al.*(1984)
		Young plantations				36-45					McCarthy and Davy (1976)
		Young plantations				26-38					Wells (1970)
		Plantations				44					Vail *et al.* (1951)
		Plantations				40					Anon. (1997)
		Stands				38-157					Van den Burg (1985)
	B	Seedlings			< 0.19						Reuter and Robertson (1993)
		Plantations				15-16					Vail *et al.* (1951)
		Plantations				10-15					Anon. (1997)
		Stands				10-29					Van den Burg (1985)
						11-25					Lambert and Turner (1977)
		Young stands				9-29					Van den Burg (1985)
					16	45					Van den Burg (1985)
	Fe	Seedlings in pot trial				49-53					Hook *et al.* (1983)
		Nursery crop				171					Donald and Young (1982)
		Young plantations				60-66					Wells (1970)
		Plantations				43-420					Vail *et al.* (1951)
		Plantations				64					Anon. (1997)
	Mn	Seedlings in pot trial				236-256					Hook *et al.* (1983)
		Nursery crop				127					Donald and Young (1982)
		Young plantations				156-295					Carter *et al.*(1984)
		Young plantations				87-165					McCarthy and Davy (1976)
		Young plantations				109-212					Wells (1970)
		Young plantations						> 1800			Van den Burg (1985)
		Plantations				135-187					Vail *et al.* (1951)
						306-392					Van den Burg (1985)
		Plantations				25-30					Anon. (1997)
E. grandis	N	Juvenile		< 0.7	1.48	1.8	1.8-3.4	>3.5			Reuter and Robinson (1997)
		Young plantations					1.8-3.4				Dell *et al.* (1995)
		Young plantations					1.48-4.42				Schönau (1981)
		plantations					2.80				Herbert, 1992
		Plantations			1.25		2.8	3.35			Herbert (1996)
		Mature		< 1	1.0	1.6	1.6-2.9	> 3			Reuter and Robinson (1997)
	P	Juvenile		< 0.07	< 0.09	0.10	0.10-0.63	> 0.30			Reuter and Robinson (1997)
		Young plantations					0.09-0.25				Schönau (1981)
		Young plantations					0.01-0.22				Dell *et al.* (1995)
		Mature		< 0.08			0.1-0.3	> 0.3			Reuter and Robinson (1997)
		plantations					0.15				Herbert, 1992
		Plantations			0.10		0.15	0.35			Herbert (1996)
	K	Juvenile		< 0.5			0.6-1.8				Reuter and Robinson (1997)
		Mature		< 0.5			0.6-1.8				Reuter and Robinson (1997)
		Young plantations					0.40-1.06				Schönau (1981)
		Young plantations	0.5	0.6			0.9-1.8				Dell *et al.* (1995)
		plantations					0.75				Herbert, 1992
		Plantations			0.36		0.75	1.19			Herbert (1996)
	Ca	Juvenile		< 0.8			0.3-1.0				Reuter and Robinson (1997)
		Mature		< 0.1			0.2-0.4				Reuter and Robinson (1997)
		Young plantations					0.46-1.27				Schönau (1981)
		Young plantations					0.3-0.6				Dell *et al.* (1995)
		Plantations					> 1.0				Herbert, 1992
		Plantations			0.56		> 1.0	1.82			Herbert (1996)
	Mg	Juvenile		< 0.6			0.1-0.35				Reuter and Robinson (1997)
		Mature		< 0.08			0.1-0.3				Reuter and Robinson (1997)
		Young plantations					0.15-0.37				Schönau (1981)
		Young plantations					0.11-0.21				Dell *et al.* (1995)
		Plantations					0.35				Herbert, 1992

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
E. grandis	Mg	Plantations			0.21		0.35	0.62			Herbert (1996)
	S	Juvenile		< 0.1			0.1-0.3				Reuter and Robinson (1997)
		Mature				< 0.15	0.15-2.0				Reuter and Robinson (1997)
		Young plantations					0.11-0.26				Schönau (1981)
		Young plantations					0.15-0.23				Dell *et al.* (1995)
		Plantations			0.10		0.20	0.29			Herbert (1996)
	Mn	Juvenile		< 8		150-220	600-700	> 1000			Reuter and Robinson (1997)
		Mature					190-700				Reuter and Robinson (1997)
		Young plantations					455-2701				Schönau (1981)
		Young plantations					193-547				Dell *et al.* (1995)
		Young plantations						151-2875			Schönau (1981)
		plantations					600				Herbert, 1992
		Plantations			129		600	6005			Herbert (1996)
	Fe	Juvenile		< 17			60-130	> 300			Reuter and Robinson (1997)
		Mature					50-156				Reuter and Robinson (1997)
		Young plantations					85-491				Schönau (1981)
		Young plantations					63-128				Dell *et al.* (1995)
		plantations					110				Herbert, 1992
		Plantations			52		110	1021			Herbert (1996)
	Zn	Juvenile		< 7			14-46				Reuter and Robinson (1997)
		Mature		< 10			15-46				Reuter and Robinson (1997)
		Young plantations					15-36				Schönau (1981)
		Young plantations					17-42				Dell *et al.* (1995)
		plantations					18.0				Herbert, 1992
		Plantations			8		18	32			Herbert (1996)
	Cu	Juvenile		< 2.0		2-7	6-15				Reuter and Robinson (1997)
		Mature		< 4			4-12				Reuter and Robinson (1997)
		Young plantations					4-23				Schönau (1981)
		Young plantations					1.7-7.4				Dell *et al.* (1995)
		Plantations			2		12	26			Herbert (1996)
		plantations					12.0				Herbert, 1992
	B	Juvenile		< 8			15-30	54-82	> 100		Reuter and Robinson (1997)
		Mature		< 12			15-100	100-180			Reuter and Robinson (1997)
		Young plantations	5	8			15-27				Dell *et al.* (1995)
		Plantations			15		32	47			Herbert (1996)
E. grandis X urophylla	N	Young plantations	0.80	1.10			1.80-2.90				Dell *et al.* (1995)
	P	Young plantations	0.09	0.10			0.15-0.26				Dell *et al.* (1995)
	K	Young plantations	0.20	0.60			0.90-1.50				Dell *et al.* (1995)
	Ca	Young plantations					0.21-0.75				Dell *et al.* (1995)
	Mg	Young plantations	0.02	0.04			0.11-0.36				Dell *et al.* (1995)
	S	Young plantations					0.12-0.29				Dell *et al.* (1995)
	Fe	Young plantations					41-98				Dell *et al.* (1995)
	Zn	Young plantations					12-29				Dell *et al.* (1995)
	Mn	Young plantations					134-2316				Dell *et al.* (1995)
	Cu	Young plantations					3.5-13.4				Dell *et al.* (1995)
	B	Young plantations	8	12			13-30				Dell *et al.* (1995)
E. nitens	N	Juvenile		< 1.3			2.0-3.5				Reuter and Robinson (1997)
		Mature		< 1.3			1.33-2.16	2.16-2.33			Reuter and Robinson (1997)
		plantations					2.30				Herbert, 1992a
	P	Juvenile		< 0.1			0.1-0.2				Reuter and Robinson (1997)
		Mature		< 0.13			0.13-0.15				Reuter and Robinson (1997)
		plantations					> 0.15				Herbert, 1992a
	K	Juvenile		< 0.4			0.8				Reuter and Robinson (1997)
		Mature		0.39-0.78			0.78-0.90				Reuter and Robinson (1997)
		plantations					1.00				Herbert, 1992a
	Ca	Juvenile					0.3-0.5				Reuter and Robinson (1997)
		Mature					0.35-0.70				Reuter and Robinson (1997)
		plantations					0.40				Herbert, 1992a
	Mg	Juvenile					0.09-0.15				Reuter and Robinson (1997)
		Mature					0.15-0.20				Reuter and Robinson (1997)

Tree Species	Element	Age, description	Visual deficiency symptoms		Low	Intermediate	Optimum	High	Toxic		Author(s)
			Observed	Threshold					Growth depression	Without growth depression	
E. nitens	Mg	plantations					> 0.10				Herbert, 1992a
	Mn	Juvenile					960-1400				Reuter and Robinson (1997)
		plantations					800				Herbert, 1992a
	Fe	plantations					> 65				Herbert, 1992a
	Zn	Juvenile		< 1.4		1.4	4.9				Reuter and Robinson (1997)
		plantations					< 23				Herbert, 1992a
	Cu	Juvenile					23-75				Reuter and Robinson (1997)
		plantations					13				Herbert, 1992a
	B	Juvenile					9-19				Reuter and Robinson (1997)
E. saligna	N	Juvenile					2.9				Reuter and Robinson (1997)
		Mature		< 0.6			0.9-2.1				Reuter and Robinson (1997)
	P	Juvenile					0.2				Reuter and Robinson (1997)
		Mature				0.07	0.08-0.2				Reuter and Robinson (1997)
	K	Juvenile					1.1				Reuter and Robinson (1997)
		Mature		< 0.4	0.45	0.80	0.85-1.50				Reuter and Robinson (1997)
	S	Mature		< 0.12			0.14-0.20				Reuter and Robinson (1997)
	Ca	Juvenile					0.6				Reuter and Robinson (1997)
		Mature					0.3-1.0				Reuter and Robinson (1997)
	Mg	Mature		< 0.15	0.20	0.30	0.20-0.40				Reuter and Robinson (1997)
	Cu	Mature					4-7				Reuter and Robinson (1997)
	Zn	Mature					16-30				Reuter and Robinson (1997)
	Mn	Mature					100-800				Reuter and Robinson (1997)
	Fe	Mature					70-86				Reuter and Robinson (1997)
	B	Mature					25-45				Reuter and Robinson (1997)
E. tetricornis	N	Juvenile		1.34			1.84				Reuter and Robinson (1997)
		Mature		< 0.8			1.00-1.57				Reuter and Robinson (1997)
	P	Juvenile					0.1				Reuter and Robinson (1997)
		Mature		< 0.10			0.17-0.25				Reuter and Robinson (1997)
	K	Juvenile					1.19				Reuter and Robinson (1997)
		Mature		< 0.7			1.1-1.5				Reuter and Robinson (1997)
	Ca	Juvenile					0.89				Reuter and Robinson (1997)
		Mature					10-1.7				Reuter and Robinson (1997)
	Mg	Juvenile					0.13				Reuter and Robinson (1997)
		Mature		0.13			0.21-0.40				Reuter and Robinson (1997)
	Mn	Mature		< 60			80-500				Reuter and Robinson (1997)
	Fe	Mature					110-425				Reuter and Robinson (1997)
	Cu	Mature		6.7			10-25				Reuter and Robinson (1997)
	Zn	Mature		< 24			32-41				Reuter and Robinson (1997)
	B	Mature					116				Reuter and Robinson (1997)
E. urophylla	N	Juvenile		0.86			1.1-3.0				Reuter and Robinson (1997)
		Young plantations					1.1-3.0				Dell *et al.* (1995)
	P	Juvenile	0.05	0.09			0.1-0.3				Reuter and Robinson (1997)
		Young plantations	0.05	0.09			0.10-0.31				Dell *et al.* (1995)
	K	Juvenile					0.8-1.4				Reuter and Robinson (1997)
		Young plantations					0.8-1.4				Dell *et al.* (1995)
	Ca	Juvenile					0.3-1.1				Reuter and Robinson (1997)
		Young plantations					0.3-0.5				Dell *et al.* (1995)
	Mg	Juvenile					0.17-0.60				Reuter and Robinson (1997)
		Young plantations					0.19-0.64				Dell *et al.* (1995)
	S	Juvenile					0.1-0.3				Reuter and Robinson (1997)
		Young plantations					0.10-0.27				Dell *et al.* (1995)
	Fe	Juvenile	9	12			33-54				Reuter and Robinson (1997)
		Young plantations	9	29			33-54				Dell *et al.* (1995)
	Zn	Juvenile	9	12			16-47				Reuter and Robinson (1997)
		Young plantations	9	12			16-47				Dell *et al.* (1995)
	Mn	Juvenile					130-660				Reuter and Robinson (1997)
		Young plantations					130-658				Dell *et al.* (1995)
	Cu	Juvenile	0.8	1.3			2-19				Reuter and Robinson (1997)
		Young plantations	0.8	1.3			1.8-19				Dell *et al.* (1995)
	B	Juvenile	7	15			16-52				Reuter and Robinson (1997)

APPENDIX 4. Summary of available temperature (°C) and rainfall (mm) data for Sonsbeek, London and Giants Castle.

Sonsbeek

	Temperature (°C)				Rain
Month	Avg max.	Avg min.	Absolute max.	Absolute min.	1997
May	22.3	-1.9	31.1	-6.8	12
June	19.8	-2.2	28.7	-9.4	117
July	19.4	-5.4	25.9	-9.9	16
August	22.8	-1.5	28.7	-8.9	26
September	24.6	2.4	34.8	-2.8	19
October	24.4	6	34.8	0.2	86
November	24.2	8.1	35.7	0.7	95
December	27.1	10.4	36.1	3.3	61
January	26.7	11.4	36.6	3.3	216
February					325
March					102
April					

London

Month	Rain '98	Rain '99	Rain '00
May	0	65.5	54.7
June	0	4.6	119
July	30.2	39.7	
August	5.7	17	
September	43.2	25.5	
October	101	37	
November	88.5	227.8	
December	287.5	203	
January	223.7	209	418.7
February	143.6	223.7	758
March	67.5	221.7	393.5
April	65	122.1	116.5

Giants Castle

Month	Rain '93	Rain '94	Rain '95	Average
May	3.5	3	12	6.2
June	0	0	1	0.3
July	0	12	0	4.0
August	4	32	0	12.0
September	28.5	2	12.5	69.8
October	179	68	62	88.4
November	73.5	43	156	110.5
December	113.5	130	235	109.8
January	146	229.5	135.5	170.3
February	153	60.5	46.5	86.7
March	94	150	149	131.0
April	46	55	27.5	42.8

APPENDIX 5 Poor growth and discolouration at Riverside (top pictures), Berlin P3 and Berlin M32 (clockwise from top left)